

GENERAL DYNAMICS
Electric Boat Division
Groton, Connecticut

Phase I Report

Evaluation OF AN AUTOMATIC SEAM TRACKING/
ADAPTIVE CONTROL WELDING SYSTEM
FOR SHIPYARD APPLICATIONS
1983 - 1984

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Department 341

Submitted to:

SP-7 Welding Panel of the Ship Production Committee
Society of Naval Architects and Marine Engineers
In Fulfillment of Purchase Order No. POM-70202-R

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EBDiv. Report No. PDE-262
February 1985

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE FEB 1985		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Evaluation of An Automatic Seam Tracking/ Adaptive Control Welding System For Shipyard Applications 1983-1984				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Surface Warfare Center CD Code 2230 - Design Integration Tools Building 192 Room 128 9500 MacArthur Bldg Bethesda, MD 20817-5700				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 81	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

ABSTRACT

An automatic seam tracking/adaptive control welding system, the M-1000, was evaluated by weld testing using the vertical position high heat input pulsed gas metal arc welding process. During the course of the evaluation period, numerous hardware and software modifications were made by the machine designer/builder, CRC Automatic Welding, in response to Electric Boat Division suggestions. Significant improvements were made in bead shape and size, and in the automatic selection of the type of bead required and the parameters to use as a function of the prevailing groove geometry.

It was concluded that the thru-the-arc concept of seam tracking/adaptive control used by the M-1000 was a viable technology and potential savings in welding time may be possible if the M-1000 could be made competitive with current mechanized systems in terms of weld quality and bead size deposited. However, additional development work, on both hardware and software, is required to realize the potential of the M-1000.

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FOREWORD

This report presents the results of an evaluation and development project sponsored in part by the SP-7 Welding Panel, one of the panels of the Ship Production Committee of the Society of Naval Architects and Marine Engineers. The equipment was purchased by the Electric Boat Division of General Dynamics under a cost sharing program with the U.S. Maritime Administration managed by Newport News Shipbuilding and Drydock Company. The principal objective was to evaluate and develop the Crutcher Resources Corporation (CRC) M-1000 Welding System for shipbuilding applications.

The technical contributions and expertise of Messrs. Joseph H. Krause and David C. Main of Electric Boat Division are gratefully acknowledged. Acknowledgement is also made to the members of the SP-7 Welding Panel, to Mr. B. C. Howser, Newport News Shipbuilding, SP-7 Panel Chairman, and to M.I. Tanner, Newport News Shipbuilding, SP-7 Program Manager.

In addition, the contributions of Crutcher Resources Corporation (CRC) Houston, Texas are acknowledged with special thanks to Floyd Thompson and his staff.

1.0 Introduction

During the last decade, semi-automatic and mechanized welding processes have been developed for many shipyard applications including gas tungsten arc welding (GTAW) for orbital and horizontal rolled pipe welding, gas metal arc welding (GMAW) and flux cored arc welding (FCAW) for hull butts and seams, and submerged arc welding (SAW) for heavy section and Panel line applications. Use of such processes and equipment has resulted in increased deposition rates, improved quality, and a reduction in overall manhours. Existing systems, however, still require considerable operator control and intervention during the welding process, or the use of extensive fixturing. Independent control of the various welding parameters requires that the operator continually monitor the weld process and take rapid corrective action to assure consistent, controllable quality and high deposition rates. Poor joint fitup hinders the operator's ability to compensate for irregular joint conditions and taxes his ability to provide maximum arc-on time, resulting in less than optimum productivity. An automated welding system capable of detecting joint conditions and welding parameter deviations, and making corrective changes in real time, would alleviate the operator's on-going problems and provide higher operator efficiency and lower welding costs. In addition, welding times and quality may also be improved by the automatic selection of the optimum welding parameters and techniques for the prevailing joint conditions.

An automatic seam tracking/adaptive control welding system was first exhibited by CRC Automatic Welding at the American Welding Society Show in April 1982. This system, designated the M-1000, was primarily designed for the pipeline industry. However, it appeared to be adaptable to shipyard applications. Its unique features included: 1) automatic thru-the-arc seam tracking; 2) automatic selection of the optimum welding parameters based on prevailing joint conditions and pre-programmed algorithms describing the welding technique; and 3) adaptive control of all welding parameters to make automatic, in process, real time corrections in welding parameters in response to changes in joint or underbead geometry. Added features provided for control of welding heat input and maintaining a constant bead fill height. Successful application of these features to shipbuilding may improve weld quality and operator factor.

A CRC M-1000 welding system was purchased under a cost sharing program between the U. S. Maritime Administration and the Electric Boat Division of General Dynamics. The principal objective was to evaluate and develop the M-1000 system for shipbuilding applications. It soon became apparent that additional hardware and software development work would be required in order to accomplish pulsed gas metal arc welding using techniques representative of those used at Electric Boat. Because of the potential benefits to the shipyard, Electric Boat elected to fund the welding phases of this development under its Manufacturing and Production Engineering Program. CRC agreed to support this effort with internal funding. It is this development work conducted by Electric Boat during 1983 and 1984 that is described in this report.

2.0 Objectives

The end objective of this program is to develop an automatic welding system suitable for shipyard use that reduces welding labor hours and if possible, support trade labor hours (such as grinding), without reducing weld quality, compared to mechanized equipment and techniques currently used.

The objective of the current phase of this program is to evaluate and modify the CRC H-1000 system to the point that it meets the end objective stated above for a limited shipyard application.

3.0 Approach

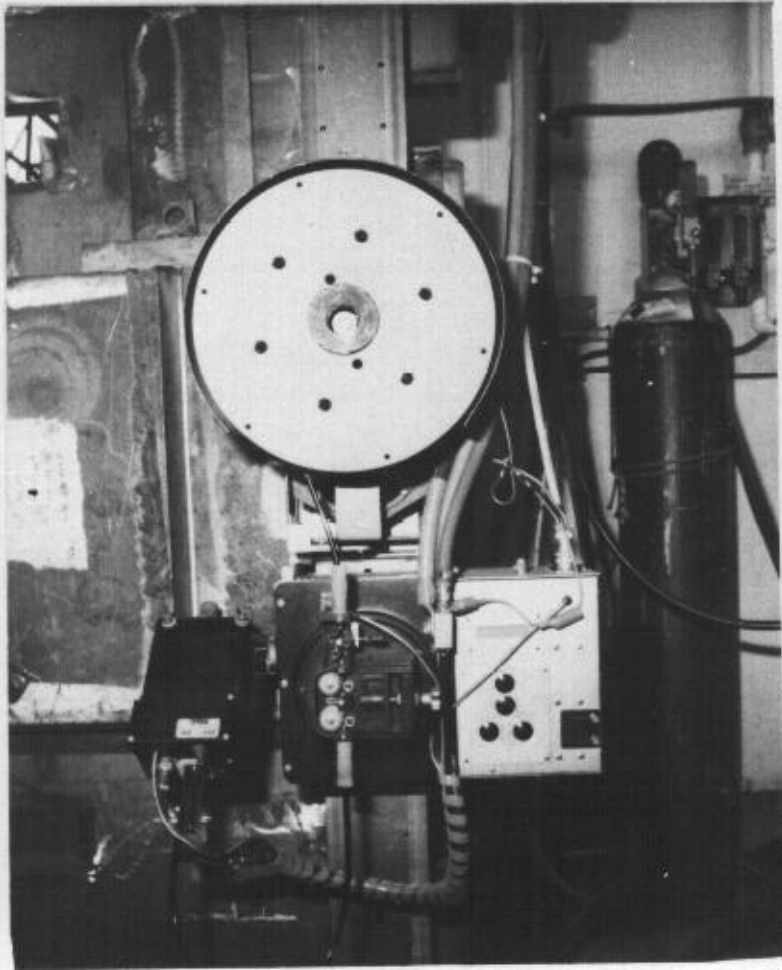
An objective equipment evaluation necessitates the establishment of reasonable performance requirements based on currently used welding equipment and techniques. Additional requirements may also be necessary to insure that welding times are really reduced without manhour increases in associated trades, such as shipfitting and grinding. After establishment of the performance requirements, evaluation of the new equipment may be accomplished by welding plates designed to test one or more of the machine's capabilities. Analysis of the results and comparison with comparable information obtained with ship yard equipment and techniques forms the basis for equipment modification and re-evaluation.

4.0 CRC System Description (March 1983)

The CRC M-1000 is an automatic, adaptive, closed-loop feedback welding system which automatically controls most welding parameters by thru-the-arc sensing. It is adaptable to the gas metal arc, submerged arc, and gas tungsten arc processes. The system consists of an integrated travel carriage/torch/oscillator unit (Figure 1) and a microcomputer with keypad which would normally be located with the welding power supply. Communication between the two units is via a high speed serial line. Also located with the welding power supply is a sense box containing a current shunt and an external contactor.

The only controls on the travel carriage are travel and wire feed jog switches, a travel forward/reverse switch, and a weld on/off switch. The torch, which is gas-cooled, uses a collet to hold the contact tip. Gas cups either a 0.625 in. I. D. ceramic nozzle or 0.43 in. by 1.1 in. elongated aluminum nozzle, are screwed into the end of the torch barrel. A solenoid mounted on the bottom of the computer enclosure controls the supply of shielding gas to the torch.

The microcomputer (8-bit RCA 1802 microprocessor) is responsible for almost the entire welding operation. This includes: selection of the initial welding parameters in accordance with preprogrammed data and algorithms describing the welding technique; sensing of joint sidewalls and underbead contour; adaptive control during the course of welding; display of information including welding parameters and joint profile information; detection of improper welding conditions; etc.



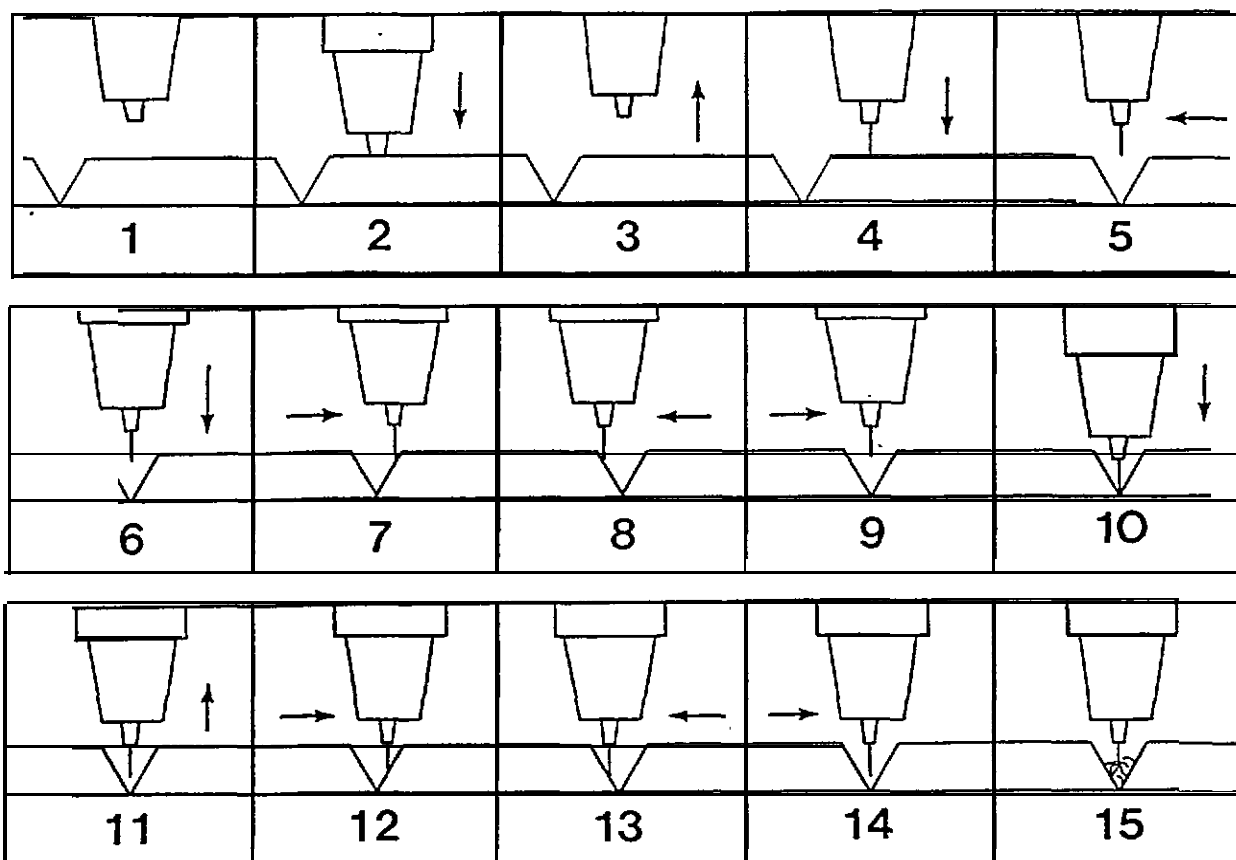
Photograph of Travel Carriage/Torch/Oscillator Unit

Figure 1

5,0 Basic Operational Theory and Startup Procedure (March 1983)

The M-1000 system is designed to select the optimum initial welding parameters based on the joint geometry at the start location and make logical adjustments in tracking and welding parameters during the course of welding. The initial parameters are calculated by the computer based on preset data (such as wire diameter, shielding gas, and maximum heat input), pre-programmed algorithms describing the welding technique (such as the relationship between bead thickness and width, travel speed, and sidewall dwells), and the joint geometry. The joint geometry at the start location is determined by a modeling routine which involves touching the contact tip or the end of the filler wire extending from the contact tip to several locations within the joint groove and on the plate surface. The computer recognizes that contact has been made with the base metal because an electrical circuit is completed. These contact points define such things as location of the plate surface, depth of the groove remaining, and slope of the sidewalls. Figure 2 shows the details of one of several modeling routines and the startup procedure.

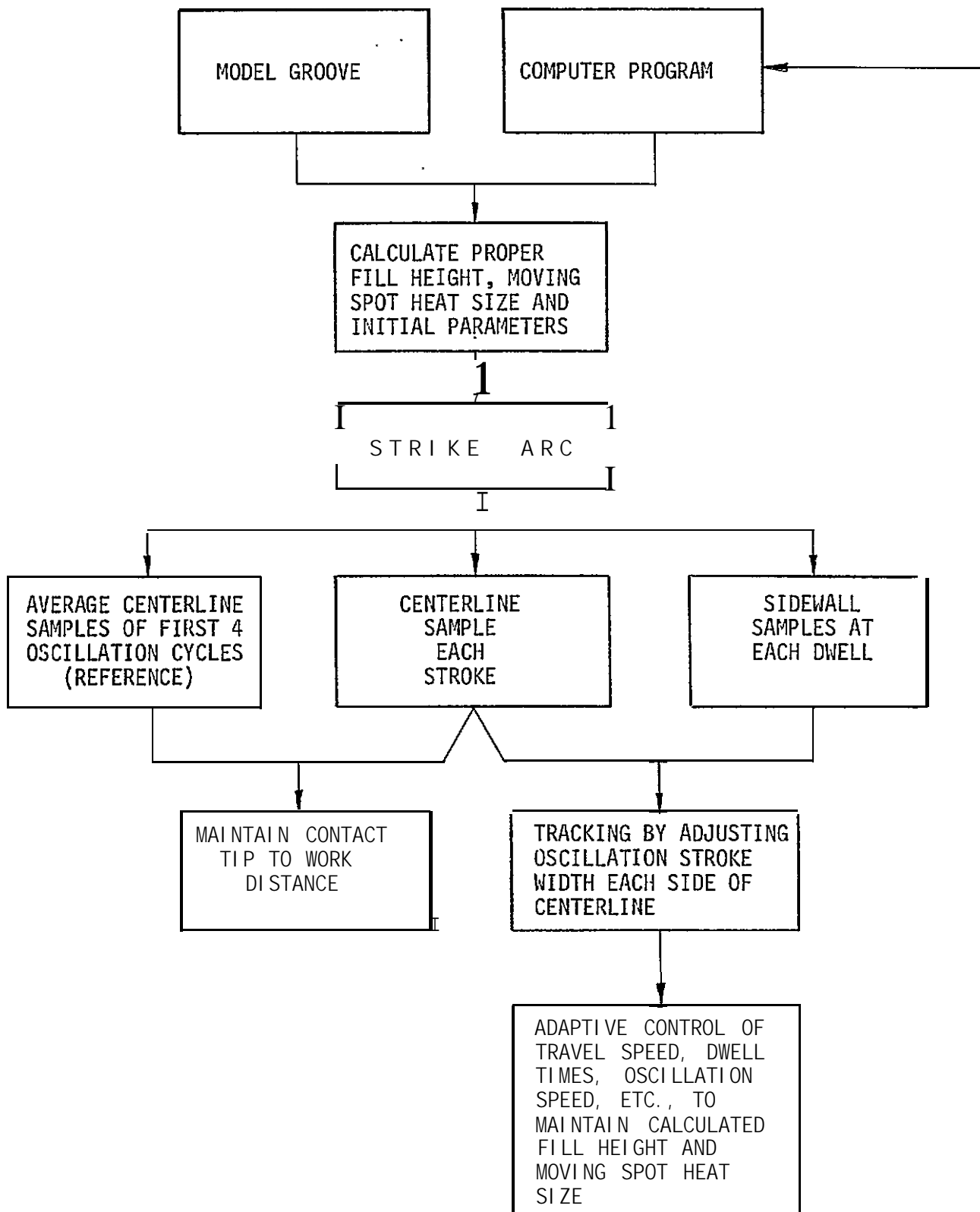
Figure 3 presents a much simplified theory of operation. Using the model of the groove at the start location together with pre-programmed constants, algorithms describing the welding technique are accessed. The computer selects the optimum initial welding parameters and establishes a range of travel speeds to optimize the fill and welding efficiency without sacrificing weld quality. With the program used at Electric Boat, each bead was to be deposited with a constant thickness regardless of changes in joint geometry along its length. This is accomplished by varying the travel speed



1. Turn weld on/off switch "on".
2. Torch rotates to preset lead/lag angle and locates surface of workpiece.
3. Torch retracts to preset contact tip to work distance.
4. Wire is fed until it contacts plate surface, establishing initial electrode stickout.
5. As torch moves over joint, operator turns off switch near center of joint.
6. Operator turns on switch and torch lowers 0.150 in.
7. Locate inside wall.
8. Locate outside wall.
9. Compute and move to centerline.
10. Locate bottom of joint.
11. Retract torch 0.100 in.
12. Locate inside wall.
13. Locate outside wall.
14. Return to centerline, compute travel speed, oscillation dwells, etc., based on joint geometry.
15. Strike arc. Adjust tracking and welding parameters by thru-the-arc sensing.

StartuD Procedure and Single Bead
Layer Modeling Routine (March 1983)

Figure 2



Theory of Operation .

Figure 3

in response to changes in groove width. However, restraints were imposed on maximum and minimum heat inputs to maximize the welding efficiency and keep the heat input at or below the maximum allowed.

After initiation of the arc, the initial pre-programmed contact tip to work distance is maintained during the first four oscillation cycles. In addition, no sidewall tracking or adaptive control is performed. Centerline current and voltage samples are taken. These values are averaged and serve as a reference. Thereafter, sidewall tracking is accomplished by analyzing and processing current and voltage signals obtained during each sidewall dwell period and comparing it to reference amperage and voltage signals extracted at the center of each oscillation stroke. In response to these signals, the oscillation stroke inboard and outboard of center is adjusted. In more detail, a quantity called AC is computed based on the change in contact tip to work distance required to give a certain change in arc power at the sidewall, knowing the sidewall slope, wire diameter, etc. This empirical quantity controls, in effect, the depth of penetration into the sidewall. During each sidewall dwell period, the difference between the change in arc power over a distance near the centerline and the change in arc power as the arc approaches the sidewall is calculated and compared to AC. If the calculated value is less or greater than AC, then it indicates that the arc is not properly located with respect to the sidewall. If this occurs, then on the next oscillation stroke the torch will oscillate 0.020 in. towards or away from the sidewall, as appropriate. If two successive corrections are made on one sidewall, no further corrections will be made, This is to prevent the possibility of the machine continuously widening the

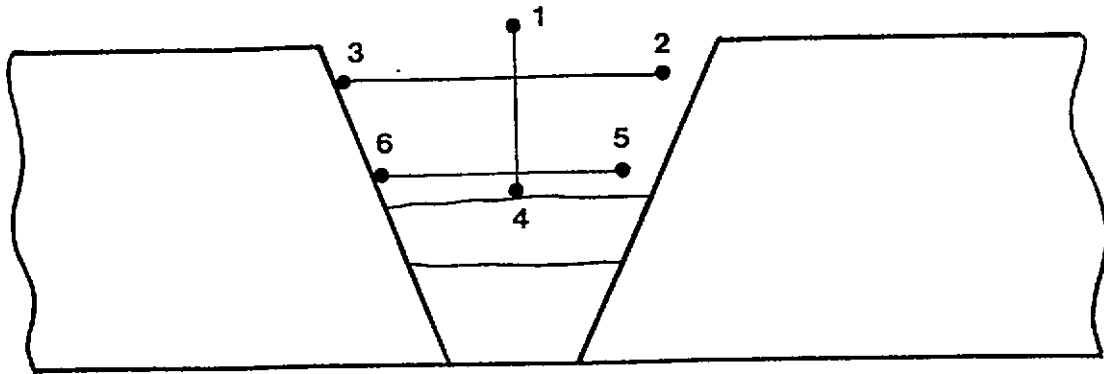
oscillation stroke in search of a sidewall that may not exist. In addition, CRC claimed that a minimum of 0.100 in. of sidewall is required for automatic tracking, Therefore, if the sidewall height fell below 0.100 in. during the course of welding, tracking on that sidewall would cease and no further changes in the extent of oscillation would occur.

Torch to work distance is maintained by comparing the current and voltage sampled at the centerline on each oscillation stroke to the reference values taken during the first four oscillation cycles. An increase in torch to work distance, such as if the depth of the groove was suddenly increased as a result of metal excavation, or if the workpiece was moving away from the welding machine, would produce lower currents and higher arc voltages at the centerline compared to the reference values. This would result in the computer driving the torch in towards the weld until the centerline samples matched the reference values.

During the course of welding, variations in the joint width are compensated for by the automatic tracking feature. The M-1000 adjusts the oscillation stroke inboard and outboard of the centerline while still maintaining a constant sidewall penetration. In response to these width changes, the travel speed is adjusted, within the limits of the allowed heat input range, to maintain a constant bead thickness and bead shape. Other parameters, such as sidewall dwells and wire feed speed, may also be adaptively changed in response to the changes in bead width and travel speed. Average arc voltage is maintained through computer control of the power supply open circuit voltage.

Ideally, no input should be required from the operator during the course of welding since the computer is performing automatic tracking and adaptively controlling all welding parameters. However, the operator has the ability to change the average arc voltage by using the keypad on the computer. This allows the operator some adjustment of the arc length to compensate for variations in wire coating, wire chemistry, contact tip condition, location of bead within groove, etc.

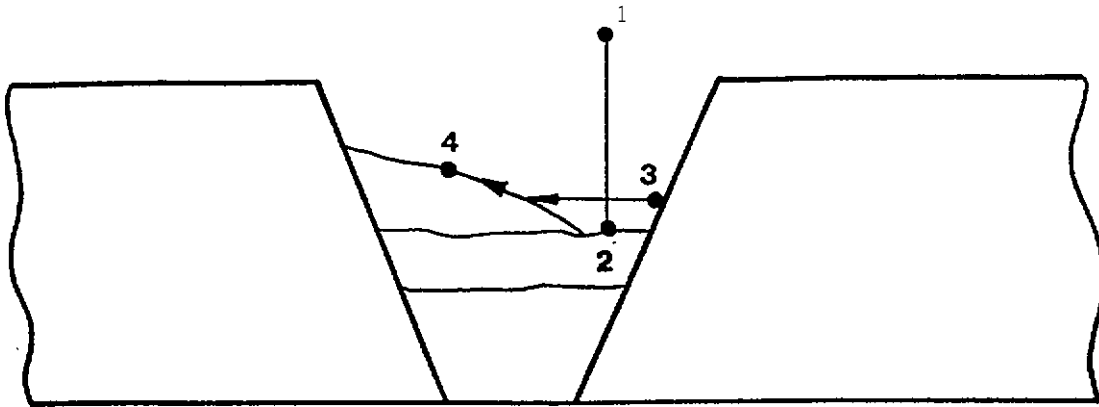
The modeling routine presented in Figure 2 was designed for single bead layer fill passes, i.e. , heads where two sidewalls of sufficient height are present. Four other routines were available to handle two bead fill layers and single and two bead finish layers. These routines are outlined in Figures 4,5,6 and 7. Figure 8 presents the single bead layer fill pass routine for comparison. Figure 4 shows the routine for a bead in a two bead fill pass layer. Automatic tracking is performed only on one sidewall; the width of oscillation is fixed and is dependent on the distance between points 5 and 6 in the figure. The routine in Figure 5 may be used for either bead of a two pass fill layer or either bead of a two pass finish pass layer. This routine is similar to that in Figure 4 except that a lower value of AC is used to reduce the amount of sidewall required for tracking. The routine in Figure 6 uses the reduced A C as in the routine in Figure 5, but allows tracking on both sidewalls. The routine in Figure 7 deposits a fixed width bead with no sidewall tracking.



1. Stop torch travel over bevel; turn switch on.
2. Stop wire short of sidewall not to be tracked; turn switch on.
3. Locate tracking Wall (upper).
4. Locate bottom of groove.
5. Stop wire at location where toe of weld should be (non-tracked side); turn switch on.
6. Locate tracking wall (lower).
7. Strike arc.

Routine for First Bead of Two Bead Fill Pass
Layer (Outboard Tracking Wall Shown)

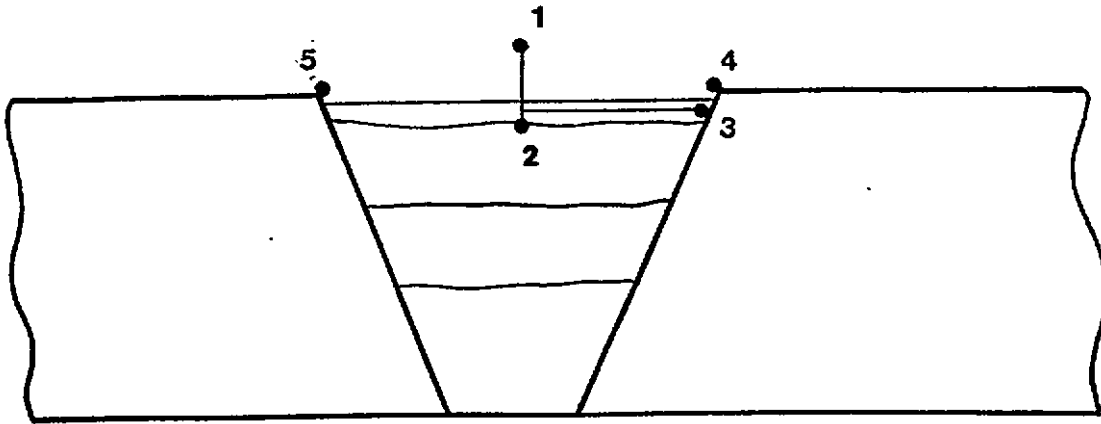
Figure 4



1. Stop torch travel over deepest part of groove; turn switch on; turn switch off; turn switch on.
2. Locate deepest part of groove
3. Locate tracking wall
4. Filler wire will trace path up existing bead surface; turn switch off at location desired for weld toe (non-tracked).
5. Turn switch on and strike arc.

Routine for Second Bead of Two Bead Fill Pass Layer
(Inboard Tracking Wall Shown) Or Either Bead of Two
Bead Finish Layer With One Tracking Sidewall

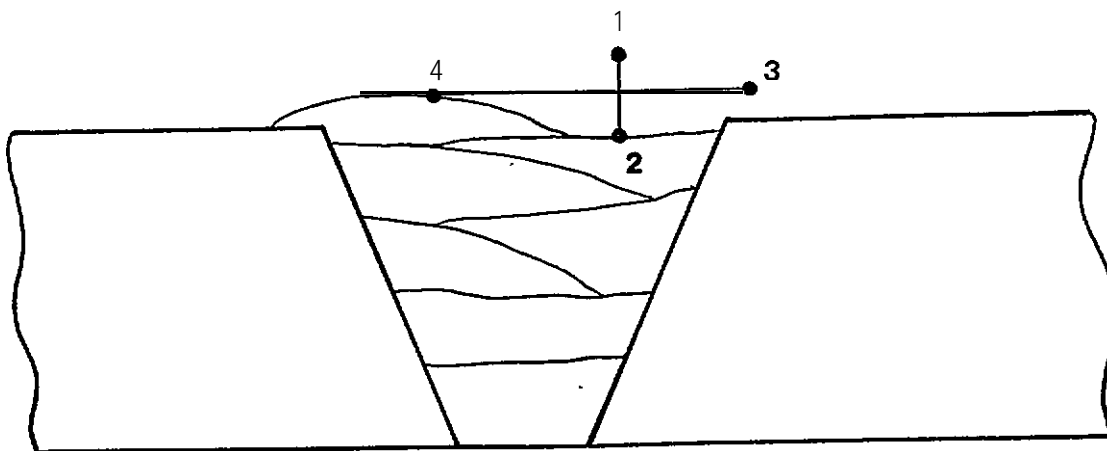
Figure 5



1. Stop torch travel over groove; turn switch on; turn switch off; turn switch on.
2. Locate bottom of groove.
3. & 4. Locate inboard sidewall; wire climbs up sidewall; stop when desired.
5. Turn on switch; as 3 & 4 above, except for outboard sidewall.
6. Turn switch on and strike arc.

Routine for Single Bead Finish Layer With Automatic Tracking

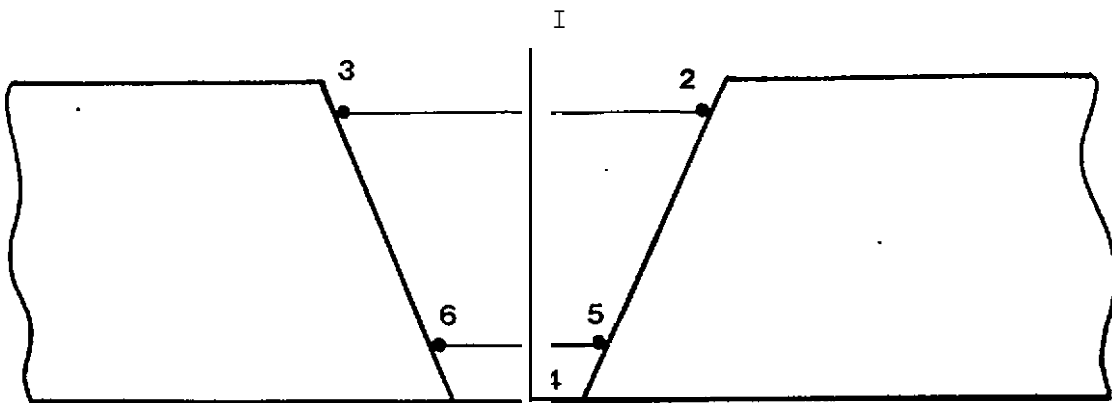
Figure 6



1. Stop torch travel over deepest part of groove; turn switch on, off, then on.
2. Locate bottom of groove.
3. Stop torch travel at desired location on inboard side; turn switch on, off, then on.
4. as 3 except on outboard side.
5. Strike arc.

Finish Layer Bead - No Automatic Tracking

Figure 7



1. Stop torch travel over bevel; turn switch on
2. Locate inboard sidewall (upper)
3. Locate outboard sidewall (upper)
4. Locate bottom of groove
5. Locate inboard sidewall (lower)
6. Locate outboard sidewall (lower)
7. Strike arc .

Single Bead Layer Fill Pass Routine

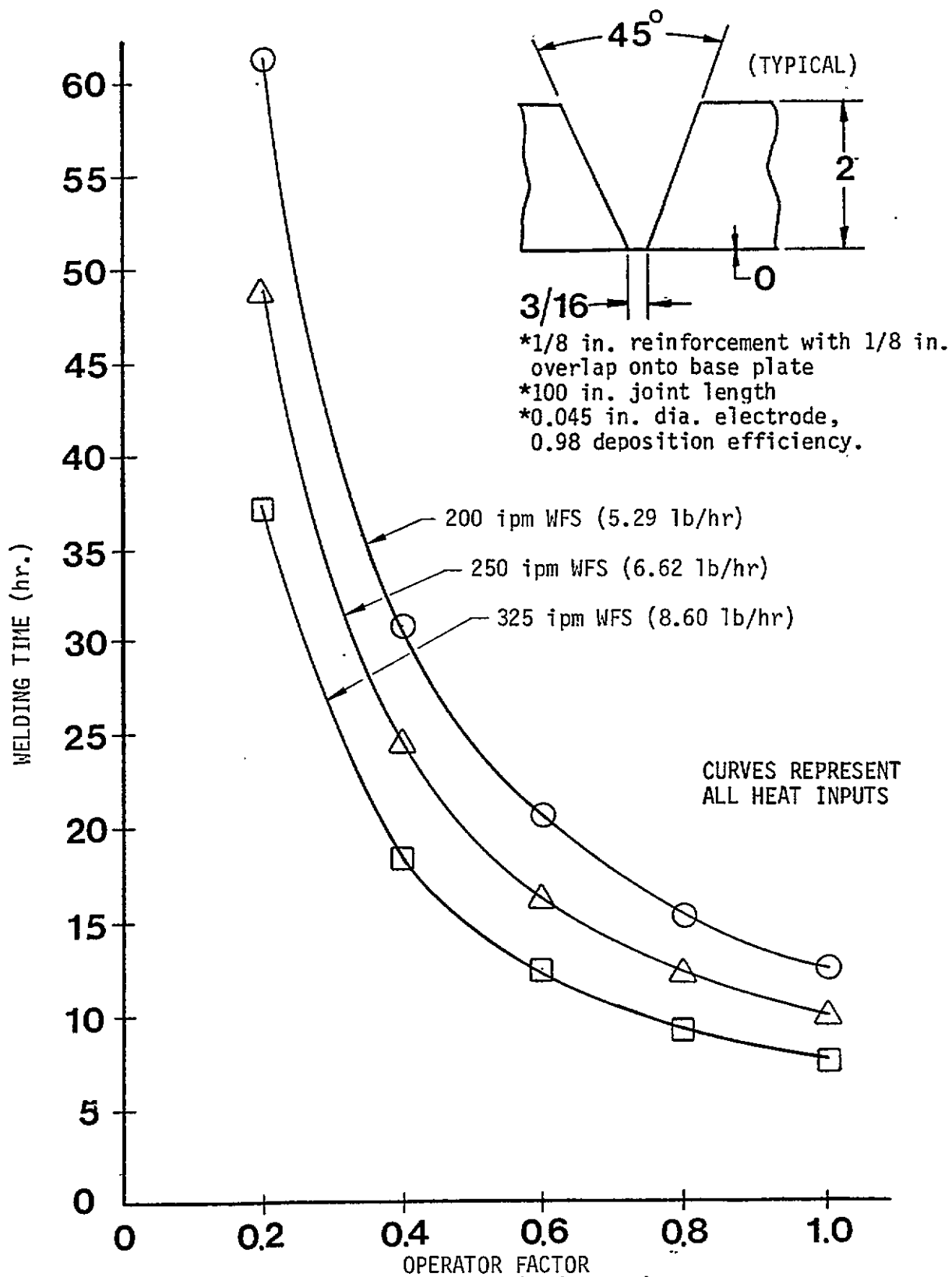
Figure 8

6.0 Summary of Expected Advantages of the M-1000

As previously mentioned, the M-1000 is designed to automatically select the optimum welding conditions based on the joint conditions at the start and perform automatic seam tracking and adaptive control of welding parameter during the course of welding. These features would hopefully improve operator efficiency and weld consistency and quality. Concurrent with the automatic tracking and adaptive control features, the M-1000 is claimed to be capable of adapting to bevel irregularities, such as sidewall gouges caused by improper flame cutting or grinding, or irregularities in the underbead surface, such as tack welds.

7.0 Criteria Used for Evaluation of the M-1000

In order to objectively evaluate the M-1000, a reasonable performance criteria was developed based on high heat input (up to 100 kJ/in) pulsed gas metal arc welding (PGMAW) practice currently used at Electric Boat Division. This practice uses 0.045 in. diameter MIL-100S-1 electrode (MIL-E-23765/2B), 95% Ar/5% CO_2 shielding gas, and 120 hertz pulse power (Airco PA-3A power supply) to weld steel in all positions at wire feed speeds up to 325 ipm (8.6 lbs. per hour net) and heat inputs up to 100 kJ /in. Figure 9 shows welding time vs. operator factor for three different wire feed speeds (200, 250 and 325 ipm) using the assumed joint design and deposition efficiency shown. Note that since the total welding time for a given joint is dependent only on the arc time and the operator factor, heat input has no effect on total welding time. Thus, each of the three lines in Figure 9 actually represents any heat input. It should be noted that the wire feed speed range of 200 to



Welding Time Vs. Operator Factor For Three Wire Feed Speeds

Figure 9

25 ipm and heat input range of 45 to 90 kJ/in. represents the practical range of conditions used in thick plate PGMAW at Electric Boat. An average welder using shipyard mechanized PGMAW equipment routinely welds vertical joints at 250 ipm (or more) wire feed speed at a nominal 90 kJ/in. The vertical welding position probably represents the largest proportion of heavy plate PGMAW performed at Electric Boat Division. In addition, it is judged to be the position easiest in which to maximize the fill rate, the heat input, and puddle control while also the easiest in which to minimize defects. Therefore, vertical position welding at 250 ipm wire feed speed was selected as a minimum performance requirement for evaluation of the M-1000.

Although Figure 9 shows that heat input for a given wire feed speed, joint design, and operator factor does not effect the welding time, actual Electric Boat Division experience is to the contrary. The reason for this is the way in which operator factor is traditionally applied, as in Figure 9. The arc time to weld a given joint is only dependent on the wire diameter, wire feed speed, and deposition efficiency. Changing the heat input (by changing the travel speed) without changing these three parameters only effects the number of beads required to fill the joint. The arc time remains the same. Thus, application of an operator factor to an arc time to calculate the welding time does not take into account any beneficial effects of higher welding heat inputs.

Increasing the heat input without changing the wire diameter, wire feed speed, deposition efficiency, or joint design results in a reduction in the welding time. The reason for this is that the welding time includes the arc time and the time between each bead. If the time between each bead and the arc time remain constant, increasing the heat input reduces the number of

beads required for a given joint. This reduces the welding time because there is less total time between beads. Figure 10 illustrates this point. For example, for a given wire feed speed, doubling the heat input halves the required number of beads. At a constant time between beads, the higher heat input procedure requires less overall welding time. The percentage savings in welding time between the high and low heat input procedures increases as the time between beads increases. This occurs because the overall contribution of interpass time to the total welding time increases as the interpass time increases. Assuming that the time between beads for the high and low heat input process variations is the same, the high heat input variation welds a joint faster than the low heat input variation.

Figure 10 also shows that for a given joint, wire diameter, deposition efficiency, interpass time and heat input, increasing the wire feed speed decreases the total welding time. This is mainly a result of the decrease in arc time.

It has therefore been shown that for a given joint, wire diameter, deposition efficiency and interpass time, welding time can be minimized by maximizing the wire feed speed (deposition rate) and minimizing the number of beads (by maximizing the heat input). Additional savings can also be realized by minimizing the interpass time. Figure 10 proves these points by considering all three variables: deposition rate, heat input and interpass time. This is the preferred method for calculating the welding time. Calculation of welding time based on deposition rate and operator factor (Figure 9) for a variety of heat inputs is possible only if the relationship between heat input, interpass time and operator factor is known for the specific application.

Thus, in order to be competitive with existing mechanized PGMAW equipment used in the vertical position, new equipment, such as the M-1000,

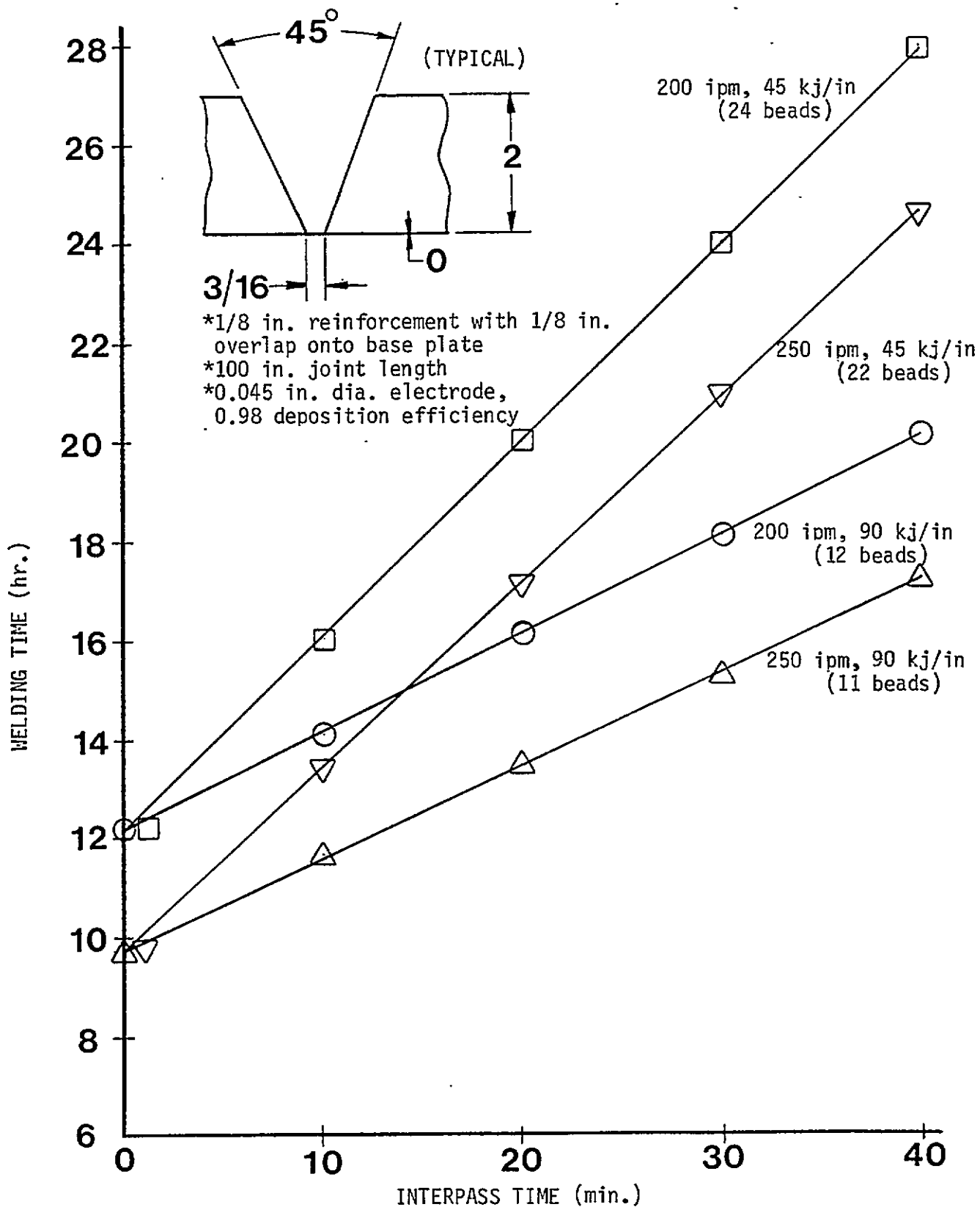


Figure 10

must be capable of depositing metal with at least the same wire feed speeds (250 ipm) and heat inputs (90 kj/in, nominal) as currently used in actual production. In addition, interpass times should not be greater than with current equipment and techniques because of more involved setup between heads, more grinding due to poor bead shapes, etc.

Several other important performance requirements must be established for the M-1000 system to be competitive with currently used mechanized equipment. These are summarized below.

- 1) The equipment must be capable of welding plate prepared in the same manner (thermal cut, ground) and with the same fitup dimensional variations (root gap, included angle, out of fairness, etc.) as normally encountered in shipyard production and weldable with existing mechanized equipment.
- 2) The contour of the beads deposited shall be such that automatic tracking and adaptive control can be accommodated. No special grinding between beads is required to allow the use of automatic tracking/adaptive control.
- 3) The welding system shall automatically adapt to bevel irregularities such as sidewall gouges, varying root gaps and tack welds, as well as varying track to work distances. The response to changes in the bevel or underbead shape shall be fast enough so that radiographic defects do not occur. The system should be capable of successfully adapting to the same degree of bevel/underbead shape variation that can be accommodated by existing mechanized equipment.
- 4) The welding system shall provide welds with radiographic and ultrasonic inspection quality at least equal to that currently attained with present shipyard mechanized equipment.

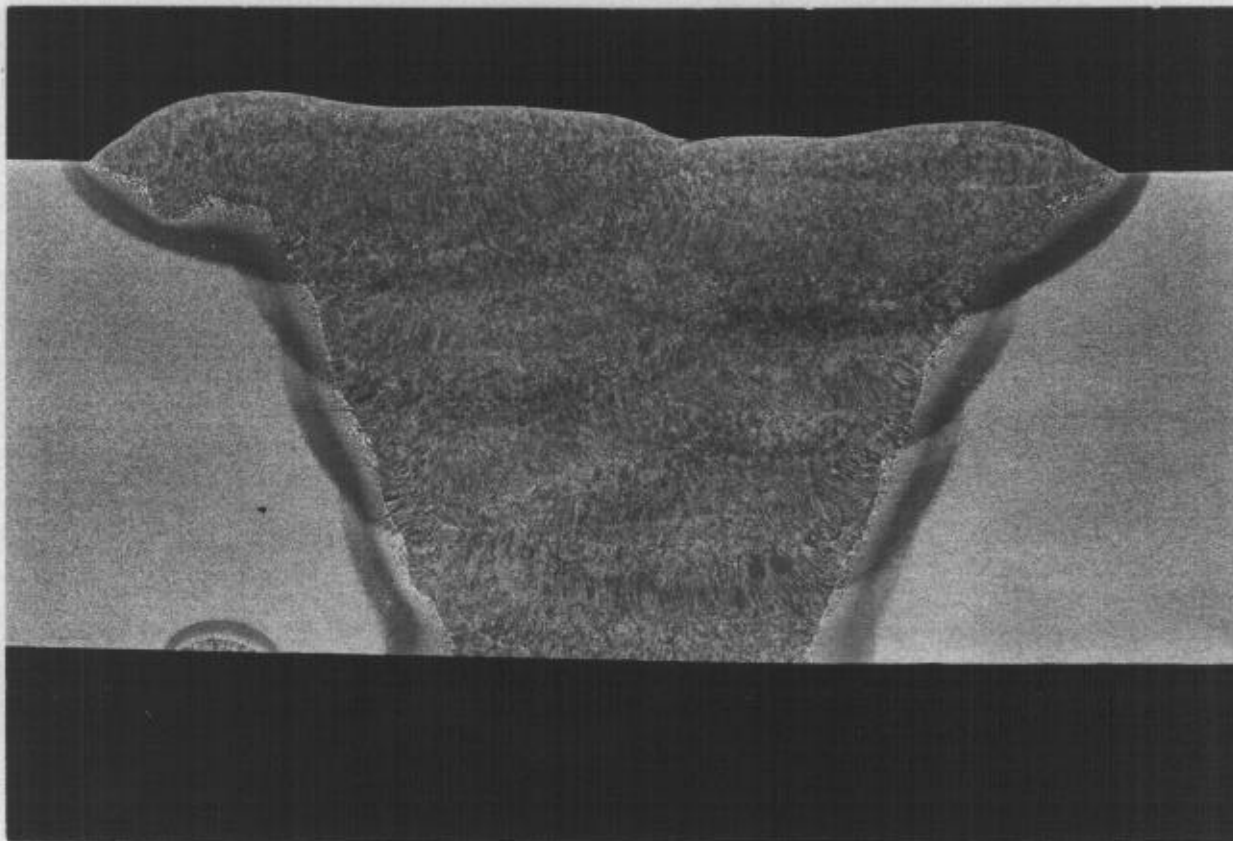
- 5) The system shall be capable of depositing root passes against backing bars, ceramic backing materials, and in open root joint configurations. All combinations of root condition and root gap normally weldable using existing mechanized equipment shall be weldable.
- 6) Weld finish passes deposited with the H-1000 shall be regular and smooth in appearance and shall blend in with the plate surface and adjacent finish passes. Reinforcement shall be a nominal 1/8 in. The number of finish passes required shall be minimized by maximizing the bead size, except in cases where the final bead required is of smaller size.
- 7) The welding system shall require a minimum of input and attention from the operator.
- 8) The welding system must be reliable and stand up to the shipyard environment.
- 9) The welding system must be serviceable by shipyard equipment repair people.

The above nine requirements and the previously discussed requirements for maximizing the wire feed speed and heat input and minimizing the time between welded passes were used in the Electric Boat evaluation of the M-1000. This is presented in the following sections.

8,0 Initial Evaluation: March 1983-December 1983

Vertical position test welds were made in 1 in. thick HY-80 steel using 0.045 in. diameter MIL-100S-1 electrode and 95% Ar/5% CO₂ shielding gas. 45° included angle single-V joints with backing bar were used. Backing bar joints were used in the initial evaluation to eliminate the many extra considerations required of ceramic backed or open root joints. Root gaps ranged from 1/16 in. to 1 in. Most work was performed at 250 ipm wire feed speed, although several initial test plates were run at 175 ipm because of the lack of software for 250 ipm.

Results of the initial testing using adaptive software were that, in general, the travel carriage was a well designed, precision unit, thru-the-arc tracking was successful, and good quality welds could be produced in standard joint designs. This is especially true at 175 ipm wire feed speed. Figure 11 shows a photomicrograph of a plate welded using 175 ipm wire feed speed adaptive software. A 5/8 in. root gap was used. Eight beads were deposited at heat inputs ranging from 76.2 to 90.0 kJ/in. no defects were detectable by radiography and contour and reinforcements provided by the finish layer beads were satisfactory. However, other plates welded with the same software were not as successful. In joints with root gaps closer to those encountered in production, such as 1/4 in., the adaptive software called for travel speeds faster than actually required. As previously explained, this results in greater welding time compared to what is possible with current mechanized equipment, especially at the relatively low wire feed speed used. In addition, it became apparent that proper finish bead contours were not always obtained using this software. In several cases, reinforcements up to 3/8 in. were obtained.



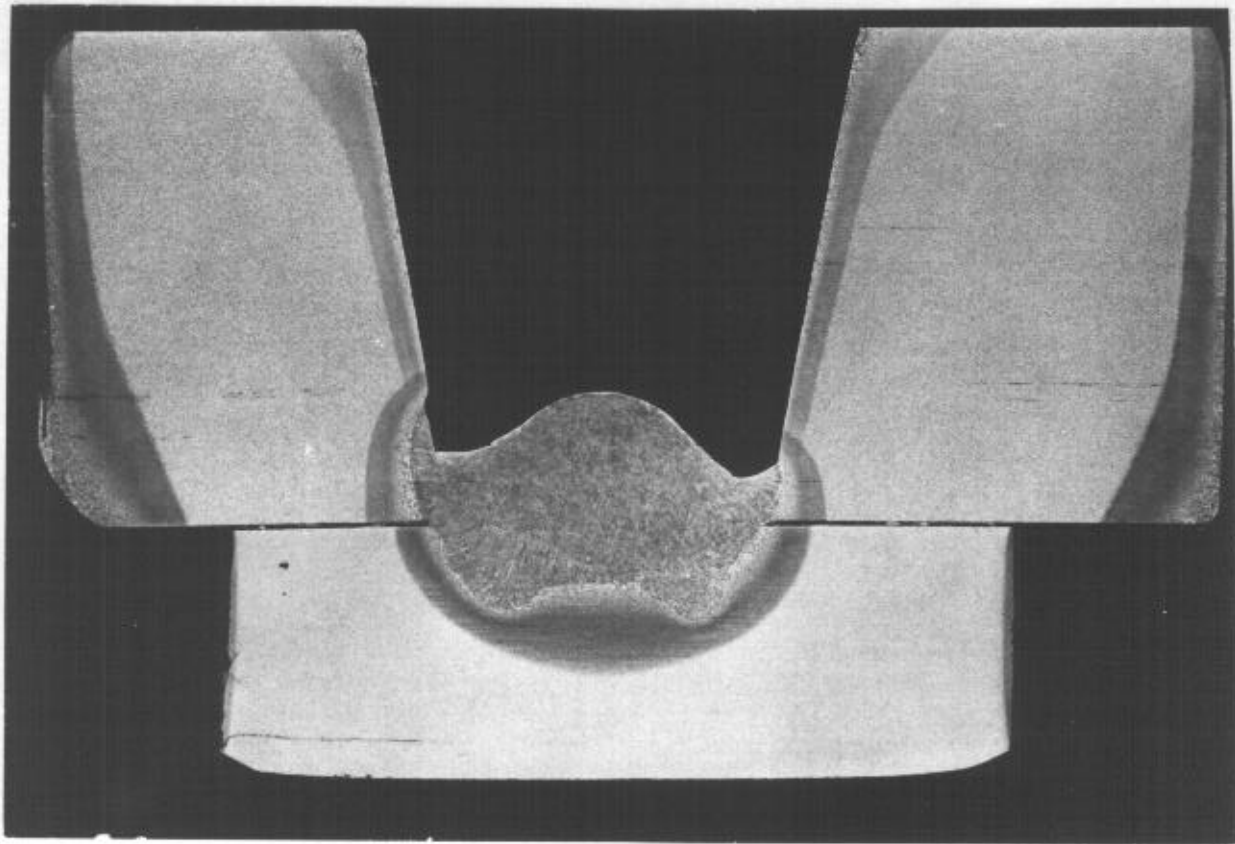
Magnification 2.5X

Photomicrograph of 1 in. Thick Weld PD 14758:
45° Included Angle, 5/8 in. Root Gap, 175 ipm
Wire Feed Speed, 76.2-90.0 kj/in Heat Input
(Adaptive Software)

Figure 11

The remainder of the initial evaluation work was performed using 250 ipm wire feed speed adaptive software. The welds produced were all of unacceptable quality, principally because of unacceptable root, fill and finish pass bead shapes, base metal undercut on root and finish pass welding, and the inability to properly track on finish passes. Figure 12 shows a representative root pass in a joint with a 1/2 in. root gap. (Note that this plate was part of a parallel program which used reduced included angles.) The bead contour features a high crown and sidewall undercut up to 1/16 in. deep (although not readily visible in the photograph). subsequent deposition of a quality bead over this root pass would be very difficult and prone to defects.

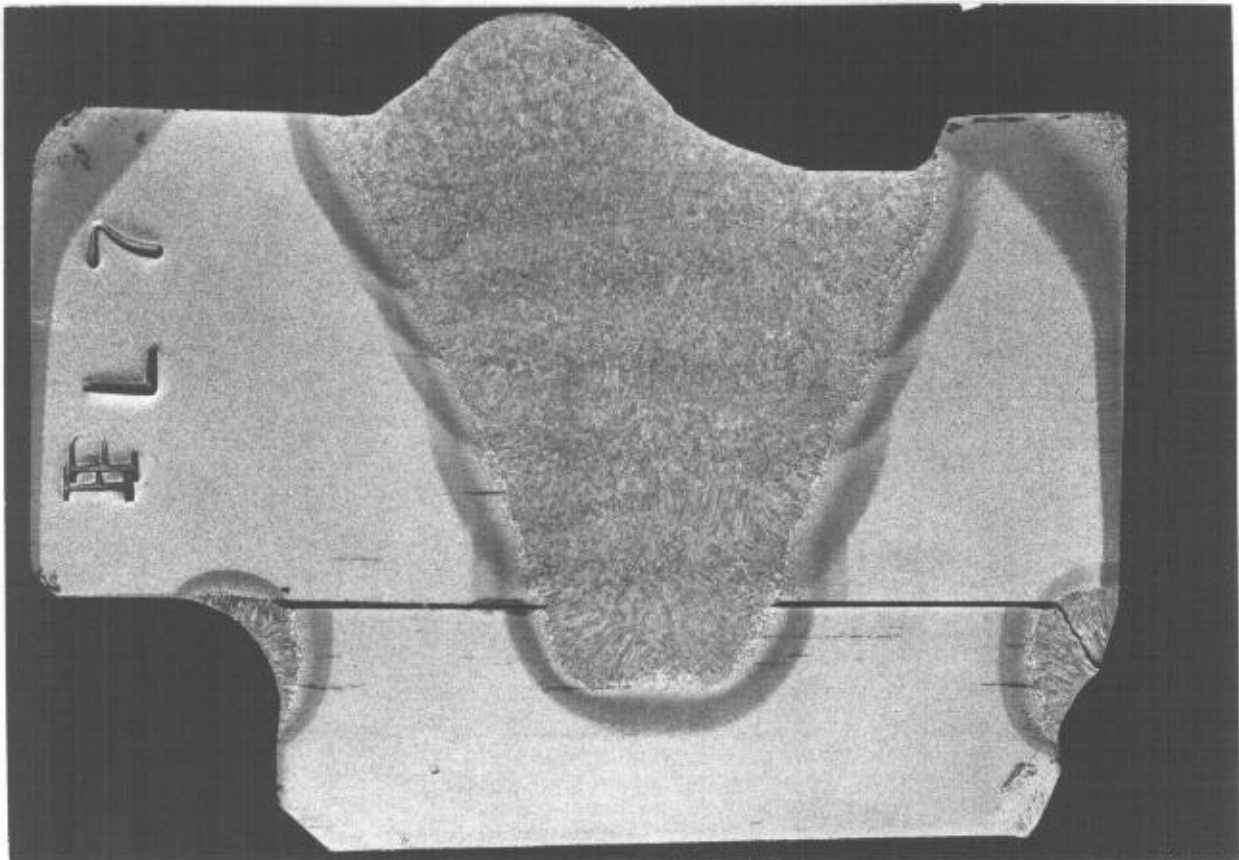
Figure 13 is a photomacrograph of a section taken from a weld where the root gap ranged from 3/32 to 1/2 in. over its 24 in. length. The root gap was approximately 11/32 in. at the point shown in the figure. The root pass had excessive convexity along its entire length, similar to that shown in Figure 12. This convexity was most severe when the root gap was between 3/32 and 5/16 in. Travel speeds ranged from 3.8 ipm at the 3/32 in. root gap end down to 2.5 ipm at the 1/2 in. end. Oscillation dwells varied as well. This demonstrated adaptive control; as the root width increased, the oscillation width increased and adjustments were made in travel speed and dwell in an attempt to maintain bead thickness and shape. After grinding off the convexity, three fill passes were deposited. These beads had acceptable contours; tracking and adaptive control appeared to function properly. After the third fill pass, the weld was 5/32 in. underflush at the 3/32 in. "root gap end and 1/16 in. underflush at the 1/2 in. root gap end. As shown in Figure 13, the first bead of a required two bead finish layer was deposited.



Magnification 2.5X

Photomicrograph of Root Pass in 1 in. Thick
Weld PD 14785: 20° Included Angle, 1/2 in.
Root Gap, 250 ipm Wire Feed Speed
(Adaptive Software)

Figure 12



Magnification 2.5X

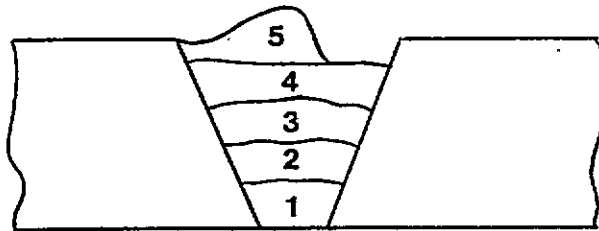
Photomicrograph of 1 in. Thick Weld
No. 7: 45° Included Angle, $11/32$ in.
Root Gap, 250 ipm Wire Feed Speed
(Adaptive Software)

Figure 13

Generally, the arc was too far from the tracking sidewall. This caused inadequate fill and undercut on that side, although not clearly visible in Figure 13. In addition, the bead shape was unacceptably convex with about 1/4 in. of reinforcement. The second finish bead was not deposited. No defects were detected in the specimen shown in Figure 13.

Although the above test plate showed promising results, several major problems were evident. The root and finish beads had poor shapes and require extensive grinding. Also, undercut may occur at the finish bead toe due to improper positioning of the arc. The convexity of the finish pass was caused by improper selection of welding and oscillation parameters by the computer. The poor root pass shape, especially at the narrower root gaps, was also caused by improper selection of welding and oscillation parameters by the computer. In effect, most of the welding heat in the root passes deposited is absorbed by the backing bar. This increases the freezing time greatly and produces a convex bead, as shown in Figure 12. In order to produce flat bead contours at the relatively high amperages and heat inputs used, the arc position must be higher up on the sidewall. This technique, which greatly decreases the freezing time, is successfully used at Electric Boat Division to maximize deposition rates and heat inputs in vertical and overhead position welding with PGWAW. Heat inputs up to 100 kj /in may be used for nearly every pass in a joint, even root passes where the root gap is at least 1/8 in. The ability to maximize the heat input for all passes reduces the number of beads required, thus reducing the total welding time. This did not occur with the M-1000, as demonstrated by the test plate shown in Figure 13 and the associated data presented in Table 1. The data in the table clearly shows that in each layer, the heat input increased as the root gap

Bead	Root Gap (in.)				
	0.16	0.23	0.30	0.36	0.47
1	58.8	60.3	72.1	89.4	89.4
2	67.1	74.1	97.7	102.3	97.7
3	72.8	75.5	81.5	92.6	97.1
4	95.0	104.0	104.0	104.0	104.0
5	76.0	76.0	76.0	76.0	76.0
Average Heat Input kj /in	73.9	78.0	86.3	92.9	92.8



Heat Input (kj/in) Per 8 bead at Various Root Gaps
(From Test Plate Shown in Figure 13)

Table I

increased. Also, as successive beads were deposited and the width of the bottom of the groove increased, the heat input increased. However, heat inputs of nearly 100 kj /in could have been used for each of the five beads over their entire length, regardless of the root gap. Therefore, the first several beads deposited in joints with relatively narrow root gap a, such as 3/8 in. or less, are done so at heat inputs well below what is possible and economical. As the root gap increases, this problem lessens. However, in relatively thin plate (such as 1 in.) with root gaps typical Of shipbuilding (0 to 1/4 in.), the M-1000 will take longer to weld the joint than currently available mechanized equipment with currently used techniques.

In addition to the problems with the bead shape and low heat input in narrower portions of the groove identified above, other problems were identified during the initial testing phase. These problems are described below.

8.1 Less Serious Problems

- 1) Electrical Component Failures: Several failures in electrical components occurred. Circuit modification and/or component upgrade solved most of the problems.
- 2) Gallling and Wear in Torch Parts: This was caused by dirt getting between two torch parts (torch carriage and torch extender) which are frequently moved to adjust the gas cup to work distance. The gallling made movement of these pieces extremely difficult. CRC coated one of the pieces with teflon which greatly reduced the problem.

- 3) Electrically Hot Areas: Several areas around the wire feeder were electrically hot and easily touched by the operator. The torch barrel and anything touching it (such as the metal gas cup previously described) were also electrically hot. This was a potentially serious problem because of the consequences of accidentally touching the gas cup to the bevel sidewall and because of internal arcing which could (and did) occur within the torch. CRC appears to have corrected this problem with insulation.
- 4) On/Off Switch Location: The original location of this switch was on the travel carriage body. This was an awkward location because parts of the wire feed system restricted its access. The switch was therefore moved to the torch assembly housing.
- 5) Keypad: The 16 key capacitive touch keypad provides the operator interface to the computer software. Using this keypad, the operator can perform system tests, input the desired arc voltage before welding, and read parameters and change the voltage during welding. It was found that the sequence of keystrokes required to perform several operations was overly long. In addition, because of the lack of tactile feedback, it was easy to enter erroneous data. CRC modified the software to reduce the required number of keystrokes, but minor problems still exist because of the lack of tactile. feedback.
- 6) Calculation of Current, Voltage and Heat Input: The computer displayed welding current and arc voltage did not match those obtained with Electric Boat instrumentation. In addition, displayed heat inputs were significantly higher than calculated based on Electric Boat

measurements. This is serious because with a maximum allowed heat input for several materials used in shipbuilding (such as HY-80, HY-100), the heat input measured as per standard shipyard techniques will be below the maximum allowed when the computer says it & at the maximum. Thus, smaller beads than possible will be deposited resulting in reduced productivity. The problem was caused by the computer using RMS current and voltage measurements in place of average current and voltage measurements traditionally used in shipyard welding. CRC changed the software to convert the RMS readings to average which has solved the problem.

Remote Voltage Adjustment: It was found that satisfactory arc characteristics were not always obtained with the target arc voltage entered into the computer prior to welding. This was probably due to several things, among which are variations in contact tip condition, variations in wire chemistry and surface condition of the wire, and fluctuations in power supply output during welding. Since the computer is supposed to be located with the power supply under actual production conditions, under most circumstances the welder would not have the ability to change the voltage. Therefore, remote voltage up and down buttons were installed on the travel carriage unit. These buttons may be operated during the course of welding and change the voltage at a more suitable (faster) rate than if the change were input via the keypad.

8.2 More Serious Problems

- 8) **Improper Travel Speed:** The travel system relies on the friction developed between two polyurethane drive wheels and a stainless steel track. Repeated measurements of the actual travel speed showed that it was "10 to 12% slower than that reported by the computer. This is serious since the algorithm that determine the optimum parameters depend on geometric calculations and if the travel speed is not correct, the bead shape will be incorrect. In addition, the actual heat input will be 10 to 12% higher, which may put the welding operation over the maximum allowed heat input that several shipyard materials require. The problem was determined to be caused by slippage between the wheels and the track. Switching to neoprene wheels did not help. Finally, the computer program was modified to account for the slippage, but the travel speeds were still about 47%. In addition, it was found that other sets of supposedly identical wheels could not be used with the same modified computer program because of speed variations up to + 10%. The wheels that produced the + 4% travel speed error were used for the remainder of the testing.
- 9) **Contact Tip Life:** Using the H-1000, an excessive rate of contact tip wear was observed. Tips lasted anywhere from 2 to 20 minutes of arc time. A tip was considered to be "worn out" when the arc quality became unacceptable. This type of problem is especially severe on the H-1000 because the operator has no recourse but to stop welding and change tips; no in-process adjustments of wire feed speed or contact tip to work distance to compensate for the tip wear are possible because

of the computer control. With standard shipyard mechanized equipment and techniques, contact tips normally last for several arc hours. Substitution of 6% tungsten/94% copper tips on the M-1000 did not help. It was also believed that because the torch was not water cooled, the contact tips could be overheating resulting in premature failure. Therefore, CRC re-designed the torch to be water cooled. Use of this torch at Electric Boat did not show any beneficial effects on tip life. Finally, grooved wire drive wheels were substituted for the knurled wheels used up to that point. Contact tip life improved greatly; tips generally lasted 20 to 60 minutes of arc time. Apparently, the knurled rolls severely cut into the surface of the wire. The wire then acted as a cutting tool as it passed through the contact tip.

- 10) Loss of Sidewall Tracking: "Using the automatic tracking finish pass routines shown in Figures 5 and 6, loss of sidewall tracking frequently occurred with sidewall heights of 3/32 to 1/8 in. With this amount of sidewall remaining, the arc easily burned away the sidewall such that with each successive oscillation stroke, the torch moved more towards the sidewall. It was concluded that with the relatively deep penetrating arc produced using high heat input PGMAW, more than the 0.100 in. of sidewall is required for tracking, contrary to the claim made by CRC. It should be noted that once loss of sidewall tracking occurs, the welder has no choice but to stop welding and restart.
- 11) Finish Pass Bead Shape: In those cases where adequate sidewall was present for finish bead tracking, the bead shape was less than satisfactory and, as previously described and shown in Figure 13, an

underfill area existed at the toe because of improper positioning of the arc.

- 12) Finish Bead Routine With NO sidewall Tracking: These passes generally had superior shape compared to automatic sidewall tracked finish passes. No underfill was present at the toes since the operator located the extent of oscillation so that it overlapped onto the surface of the base plate. However, a major problem with this routine was that no changes in centerline position or bead width were possible once the arc was struck. Therefore, if the groove width changed along the weld length, the operator could not make the appropriate change in bead width. Likewise, if the edge of the bevel was not parallel with the track, the appropriate adjustment in bead location could not be made.
- 13) Routine Setup Problems: As shown in Figures 4 to 8, several routines exist for depositing root/f ill pasaes and finish passes. It is the responsibility of the operator to select the appropriate routine. In addition, the operator is responsible for determining the oscillation width in the routines where only one sidewall is tracked. All the routines, except for the single bead layer fill pass routine (Figure 8), were judged to be difficult to set up because of the number of operations requirad of the on/off switch. Also, it was difficult for the operator to judge where to place the filler wire without seeing the actual weld puddle. It was also very difficult to stop the filler wire exactly where the operator wanted it. If it is stopped at the wrong location, the routina must be started over again. Therefore, less than optimum bead shapes resulted. Again, because of the computer control, the operator's only choice was to stop welding if the bead shape was not proper.

- 4) Starting Problems: Arc startup frequently resulted in poor initial bead shape and porosity. This problem was caused by the torch maintaining a preset contact tip to work distance during the first four oscillation cycles. During this period, adjustments in width are not performed. After this initial period, tip to work and width adjustments are made, but they may not reach their proper values for several oscillation cycles. During this time, the M-1000 is traveling forward. Thus, a portion of weld may not have proper bead shape. In addition, the gas cup to work distance may be such that porosity results and, because of a less than ideal tip to work distance, proper fusion may not occur in the root or with the underbead surface.
- 15) Restarting Problems: The four oscillation cycle sampling and the delay in assuming proper tip to work distance and oscillation width proved to be a severe problem on arc restarts. It frequently appeared that lack of fusion with the underbead surface occurred. In addition, it was necessary to model the joint at the point where the arc was to be restarted. This was usually on the crater (dressed by grinding) of the weld stop. However, because of the rapid change over a short distance in underbead width and depth on going from the crater to the previous bead surface, adjustments in tip to work distance and width were delayed long enough (during the initial 4 oscillation cycles) so as to produce doubtful fusion (See Figure 14).
- 16) Slow Tracking Response: A possible problem was found when the depth of the groove suddenly increased, such as when welding into a ground area or welding over a tack and the end of the tack is reached. The second

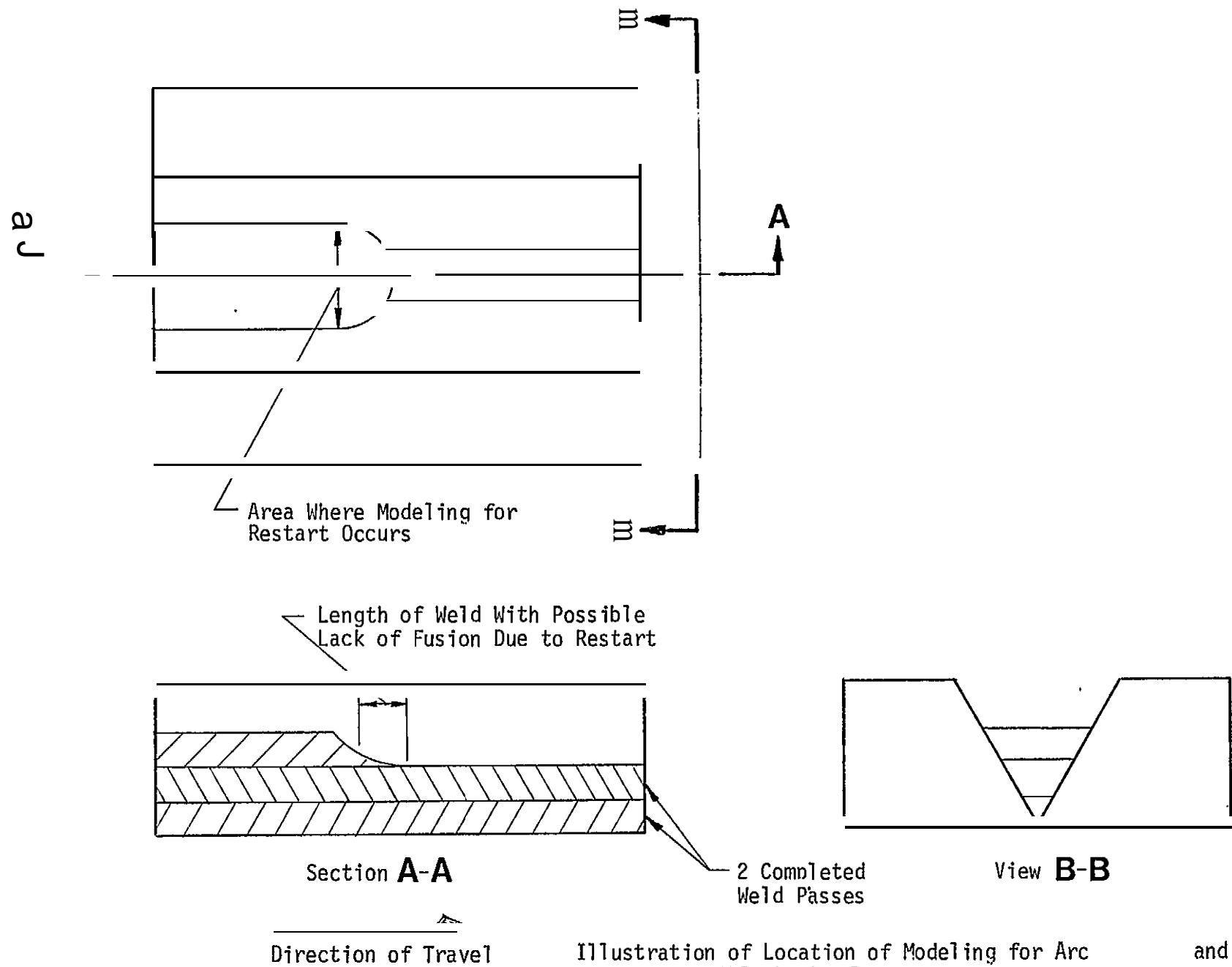


Illustration of Location of Modeling for Arc Area of Possible Lack of Fusion.

Figure 14

and

example is particularly severe and is similar to the situation for restarting on a weld crater as shown in Figure 14. As the arc comes down off the tack, the depth of the groove increases. Because it takes several oscillation sweeps for re-adjustment to the proper contact tip to work distance, a long "soft" arc exists until the adjustment takes place. During this time there is questionable underbead fusion. On the other hand, if welding was proceeding from a low area onto a high area, (opposite direction of travel shown in Figure 14), good fusion takes place even though there is the same delay in re-adjustment in tip to work distance. This occurs, because during the transition, the arc does not lose penetrating power since the tip to work distance is shorter than called for instead of longer than called for.

There is also a potential problem with tracking rapid changes in sidewall contour, such as going into a sidewall gouge caused by improper flame cutting. A limited amount of testing was performed using ground sidewall gouges approximately 1/8 in. deep by 1/4 to 7/16 in. long. It appeared that the H-1000 could not always be counted on to make the required adjustments in the extent of oscillation to successfully weld the gouges. Considering a typical travel speed range of 1.6 to 2.0 ipm, an oscillation width of 0.3 to 0.7 in., an oscillation velocity of 0.75 in. per second, and sidewall dwells of 0.6 seconds, the arc travels between 0.05 and 0.10 in. forward each oscillation cycle. Because there is a one oscillation cycle delay between when the need to change the extent of oscillation is detected and when the correction takes place, the arc may have traveled past the point where it could successfully fuse the leading edge of the gouge. This is especially true if on the

oscillation sweep before the need to change is detected, the leading edge of the gouge is nearly under the arc, but the change in geometry isn't radical enough to call for an oscillation change. These potential problems may be compounded by the fact that only 0.020 in. of correction in the extent of oscillation is allowed per aweep on each aide of centerline for a maximum of up to two successive corrections on each side. Thus, if a 1/8 in. deep by 1/4 in. long sidewall gouge was present, and its presence was detected at its leading edge, after two successive corrections the extent of oscillation will have moved 0.040 in. closer to the sidewall while the machine has moved forward 0.05 to 0.1 in. This correction may or may not be enough to successfully weld the gouge.

- 17) Joint Cleaning Requirement: The modeling routines performed prior to welding rely on the electrode touching different areas on the plate surface and within the weld groove and completing an electrical circuit. If poor contact is msde when the electrode touches the joint, the circuit will not be completed and the torch will continue traveling. When this occurs, the circuit is frequently completed as the extra pressure imposed by the excess torch excursion forces electrical contact. However, because the sidewall is located by how far the torch physically traverses, this location will be improper. If this is not noted by the operator and the modeling routine is allowed to continue, improper bead shape may result. Therefore, it is extremely important to thoroughly clean the area in the vicinity of the start to remove all signs of oxide and slag. Unfortunately, power wire brushing may not

fully remove all the slag between the weld ripples; light burring is usually required.

9.0 M-1000 Upgrade (December 1983-April 1984)

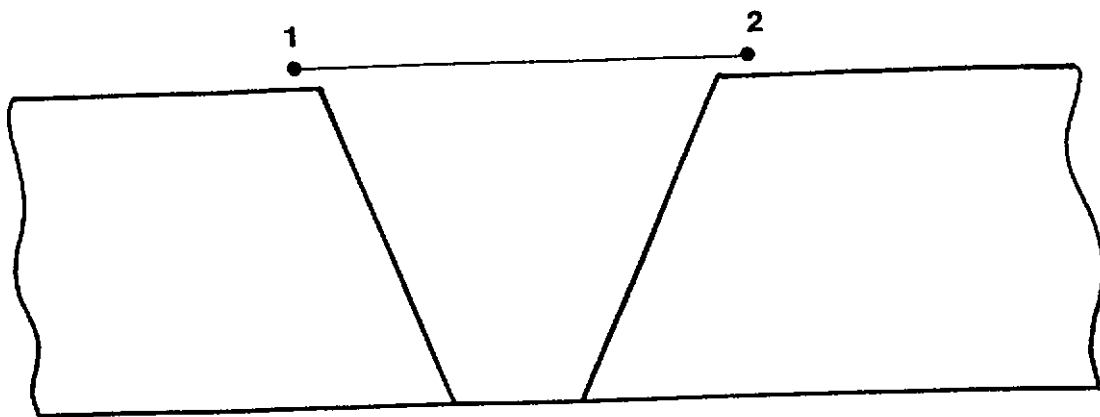
During the initial evaluation period, numerous discussions and meetings between Electric Boat Division and CRC Automatic Welding were held to evaluate the project progress and to try to solve the many technical problems. It was agreed that a major upgrade in the software was required to enable the M-1000 to run optimized procedures for 250 ipm wire feed speed and to simplify the setup routines to the point where all of the major decisions would be made by the computer. This software upgrade also required a hardware upgrade in the computer to accept additional EPROM chips and in the travel carriage to accept additional controls for oscillation width and centerline position. What follows is a description of the key points of the upgrade.

Setup Routines

As previously discussed, the setup routines were clifficult to use and the operator was responsible for determining what type of bead was called for (split fill, single bead fill, etc.). It was proposed to solve these problems by upgrading the joint modeling performed by the M-1000 to the point where the computer would make the decision as to the type of bead required. This would also allow the use of a single setup routine. These changes would make the operator's job easier and eliminate the chance of making improper decisions concerning bead width, type of bead required, etc. Thus, this improvement has the potential for savings in welding time through automatic selection of the optimum type of bead.

The new setup routine follows Steps 1 to 4 in Figure 2, but is much simpler thereafter. After Step 4, the torch moves outboard toward the bevel. The operator must stop the electrode about 1/8 in. inboard of the top inboard corner of the bevel (Figure 15). As with the previously discussed routines, the traverse of the torch is started and stopped with the weld on/off switch. If the operator over or undershoots the proper location, inboard and outboard torch centerline adjustment buttons, now present on the upgraded M-1000, may be used to adjust the position. The on/off switch is turned on and the torch drives in until the electrode touches the plate surface. Then the same operation is performed for the outboard side. This is the only part of the setup routine the operator is responsible for; the rest is automatic. Note that with the plate surface located on each side of the bevel, the computer has the ability to calculate the area of the remaining groove based on modeling performed within the groove and a reference line joining the two surface locations.

The automatic portion of the setup routine models the joint to the extent necessary to determine what type of bead is required, where it should be located, and what the welding parameters should be. If it determines that enough sidewall is present for tracking, then a short modeling routine is performed to determine if a single bead layer can be deposited. This decision is based on the calculated single bead width not exceeding a pre-programmed value. If a single bead cannot be deposited, then a more extensive modeling routine is performed to fully characterize the contour of the underbead surface. A split bead is then automatically deposited on the deeper side of the bevel. The oscillation width is fixed at 75% of the width



1. stop torch travel so electrode is $\frac{1}{8}$ in. from inboard bevel edge. Use centerline position adjustment buttons to shift position, if required.
2. Turn switch on; wire touches plate; torch retracts and travels outboard. Stop at location 2.
3. Turn switch on; wire touches plate; groove modeled automatically.

Upgraded M-1000 Modeling Routine

Figure 15

of a hypothetical single bead layer deposited at that location or a pre-determined maximum split bead width, whichever is less. The pattern of split beads continues until it is determined that not enough sidewall exists for tracking. With between 0.350 and 0.200 in. of sidewall remaining, a last fill routine is automatically run. In this routine, the computer deposits single or split beads, as appropriate, but does not perform automatic tracking. "Optimum" parameters, however, are calculated and set by the computer before the arc is struck. In this "manual tracking mode", the operator uses the width and centerline position adjustment buttons to make appropriate adjustments. Adjustments in travel speed, dwell, etc., are not possible. The value of this routine is that it theoretically permits the automatic selection and running of the optimum parameters and maximum heat input where sidewall conditions have a chance of becoming unsuitable for automatic tracking at some point.

If the detected groove depth is less than 0.200 in. then the finish routine is automatically run. The object of this routine is to deposit a finish layer with a nominal 1/8 in. reinforcement in as few passes as possible. Through the use of detailed modeling of the underbead surface, the computer determines if one or more passes are required. When more than one head is required, all beads but the last one are deposited at the maximum pre-programmed heat input to reduce the number of beads required. The oscillation width of each bead is automatically set to produce a nominal 1/8 in. reinforcement. If the maximum heat input is not required on the final pass of a multi-bead finish layer, that bead is deposited at a lower heat input. However, the minimum width of this last bead is 1 in. to control the bead shape. Compared to the finish pass routines previously discussed,

underfill and/or base metal undercut is less likely to occur with this upgraded routine because the arc is brought up onto the surface of the base plate, about 1/8 in. from the top corner of the bevel. It should also be noted that the operator has the ability to adjust bead width and centerline position within certain limits during the course of welding through use of buttons mounted on the travel carriage.

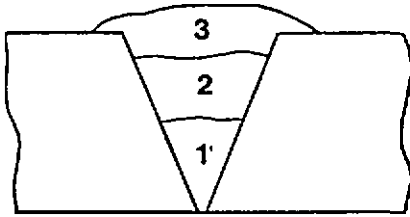
In summary, with the upgraded routine, only one setup procedure is required, regardless of the type of bead required. The computer automatically determines the type of bead required and the optimum parameters. With less than 0.350 in. of groove depth remaining, optimum parameters are set by the computer, but no tracking is performed. In this case, the operator has control of the bead width and centerline position (within certain limits). On finish passes, parameters are set by the computer to produce a nominal 1/8 in. reinforcement height.

Bead Shape and Size

One of the conclusions from the initial evaluation was that beads were frequently deposited at heat inputs far less than routinely used with mechanized equipment. In addition, bead shapes were not always satisfactory. Therefore, revised algorithms describing the welding technique were developed to improve bead shape and size. To facilitate the development of the improved algorithms, Electric Boat Division welded vertical position test plates at 250 ipm wire feed speed using the M-1000 and a special program that allowed manual input and control of all welding parameters. 45° included angle single-V joints were welded at what was considered to be optimum parameters (maximum possible heat input, best possible bead shape) for root gaps of 1/16, 1/8, 1/4, 3/8, 1/2 and 1 in. For each bead of

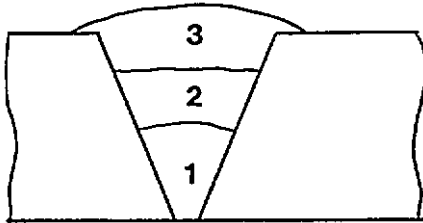
each plate, measurements of bead thickness and width were made. Table II shows the bead pattern and heat input used for each plate. (It should be noted that at times the 100 kj /in heat input limit was exceeded because of the inaccuracy of the M-1000 travel speed). Figures 16, 17 and 18 are macrosections removed from three of the plates. All six plates met magnetic particle (backing bar removed) and radiographic inspection requirements. This data, along with other parametric data from previous EBDiv. work, were supplied to CRC and aided in the development of improved welding technique algorithms.

The six plates discussed above proved that the M-1000 was capable of depositing sound weld metal with good bead shapes at maximum heat inputs if the welding parameters are selected and controlled by the operator. Translation of the optimum welding parameters into algorithms is not an easy task because aspects of the welding technique must also be considered. Four areas of technique of particular importance are: single bead root passes; single and split bead fill passes; and finish passes. A good single bead root pass over a backing bar is deposited at the maximum feasible heat input, provides full root fusion, and is not overly convex or concave in shape. The technique used varies with the root gap. For a constant wire feed speed, as the root gap decreases below a certain value, the travel speed must generally increase to prevent the arc from riding excessively high on the puddle. In addition, it is beneficial to decrease the contact tip to work distance to increase the penetration. As shown by the data in Table II, it is possible to deposit successful root passes at over 80 kj /in heat input if the root gap is at least 1/8 in. Below 1/8 in. root gap, the travel speed must be increased to insure full penetration. For all of the root gaps represented



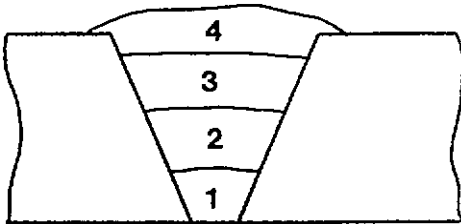
1/16 in. Root Gap

Bead	1	2	3
Heat Input (kj/in)	54	87	90



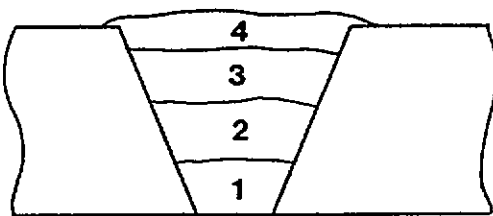
1/8 in. Root Gap

Bead	1	2	3
Heat Input (kj/in)	89	95	100



1/4 in. Root Gap

Bead	1	2	3	4
Heat Input (kj/in)	86	104	96	99

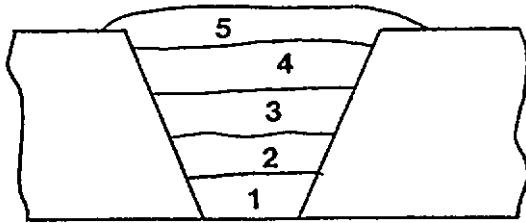


3/8 in. Root Gap

Bead	1	2	3	4
Heat Input (k.j /in)	85	99	99	110

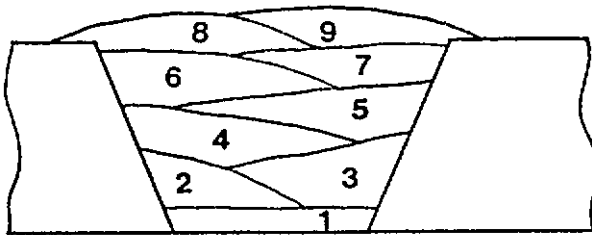
Bead Patterns and Heat Inputs: Optimum
Parameters and Heat Input - Manual Input Program

Table II



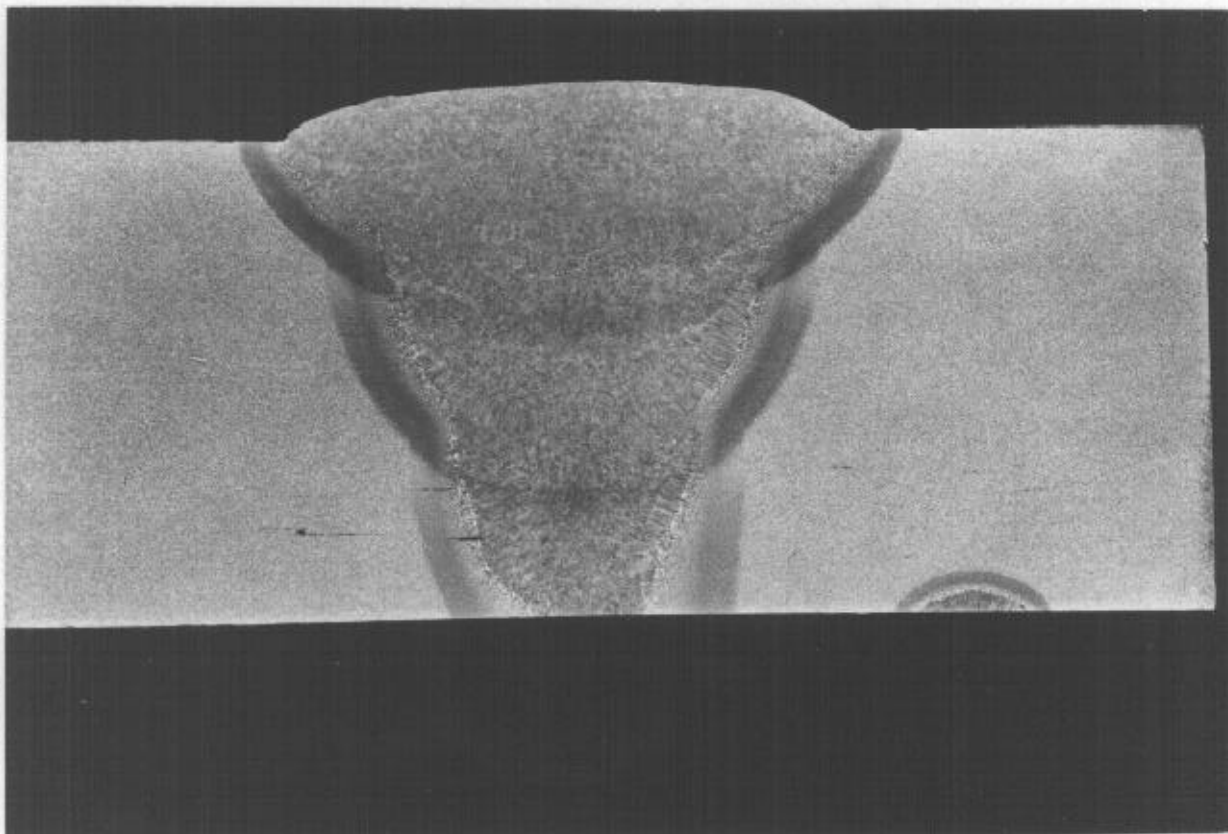
1/2 in. Root Gap

Bead	1	2	3	4	5
Heat Input (kj/in)	83	94	91	89	96



1 in. Root Gap

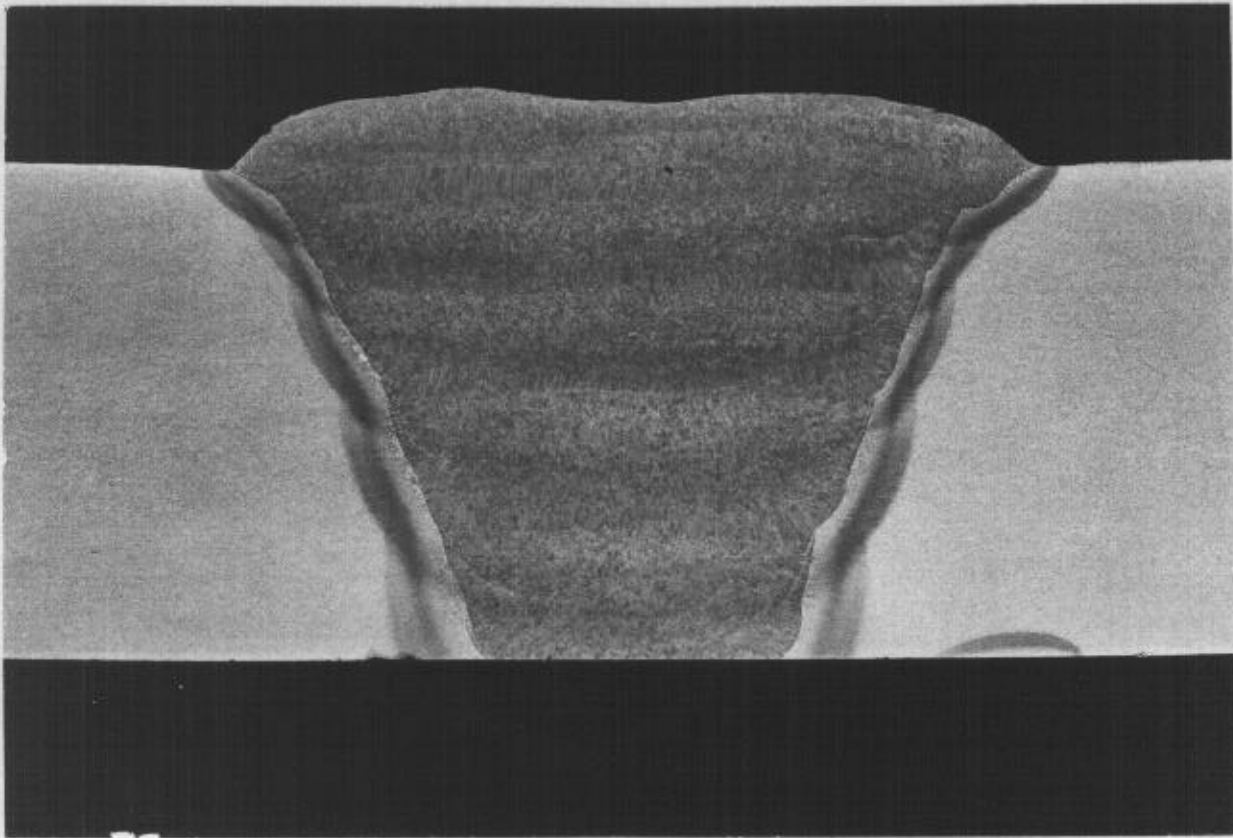
Bead	1	2	3	4	5	6	7	8	9
Heat Input (kj/in)	100	95	92	92	93	95	93	80	68



Magnification 2.5X

Photomicrograph of 1 in. Thick Weld
PD14875: 45° Included Angle, 1/16 in.
Root Gap, 250 ipm Wire Feed Speed
(Manual Input of Parameters)

Figure 16



Magnification 2.5X

Photomicrograph of 1 in. Thick Weld
PD14881: 45° Included Angle, 1/2 in.
Root Gap, 250 ipm Wire Feed Speed
(Manual Input of Parameters)

Figure 17



Magnification 2.5X

Photomacrograph of 1 in. Thick Weld
PD14909: 45° Included Angle, 1 in.
Root Gap, 250 ipm Wire Feed Speed
(Manual Input of Parameters)

Figure 18

in Table II, the oscillation parameters were adjusted to provide for a relatively flat bead contour while still allowing full penetration. Thus, there is a delicate balance between penetration, bead shape, and bead size. In order to maximize the heat input and maintain a good bead shape, the arc must impinge on the sidewall to provide a sufficient heat sink. However, if too much of the arc energy is absorbed by the sidewalls, penetration will be reduced. In addition, if the arc characteristics are not proper (such as arc too soft, too broad, too long), penetration will be reduced. Differences of 1/16 in. in root gap may greatly change the parameters and technique required. Therefore, algorithms which accurately reflect root pass parameters and techniques are essential for successful root pass welding using the M-1000.

The sensitivity of single and split fill pass bead shape and quality to the exact parameters and technique used is slightly more forgiving than for root passes, but a fine balance still exists between parameters that produce good beads and those which produce unacceptable beads. Heat inputs in excess of 90 kJ/in are almost always usable for the first fill pass over the root, and in fact, for all additional single bead layer fill passes. However, in order to maintain a flat bead contour, the arc must be properly positioned with respect to the sidewall and proper oscillation parameters are required. As the groove width increases, the bead thickness for a given travel speed decreases. As this occurs, the proper positioning of the arc and oscillation parameter requirements change.

To deposit successful split bead fill passes with maximum bead size, location of each bead with respect to the sidewall and bead shape are critical. In the Electric Boat technique, all split passes are deposited in such a way and with such a shape to allow use of heat inputs in excess of 90 kJ /in for each bead. Again, oscillation parameters and arc location are critical.

Deposition of successful finish passes is also challenging because the bead shape is very sensitive to the oscillation parameters and the underbead contour at the high heat input used. Deposition of unacceptable finish passes featuring high crowns or excessive reinforcement, undercut, or underfill will result in extensive rework.

In summary, successful high heat input PGMAW is highly dependent on oscillation parameters, arc characteristics, and technique. Development of algorithms which accurately describe the welding procedure are essential for successful application of the M-1000. Algorithms which produce good quality beads at heat inputs below that possible with mechanized equipment or algorithms which produce beads of size equal to those possible with mechanized equipment, but with poor bead shape or defects, are unacceptable.

Change to Constant End Face Volume Routine

As previously discussed, the H-1000 was programmed to maintain a constant bead thickness, within the limits of the allowed heat input range, even though the groove geometry might change during the course of welding. Although this may appear desirable, it may actually result in a problem if welding is performed over tacks or excavations. Considering the case of tacks, the H-1000 is programmed with the ability to deposit a continuous root

pass regardless of any small tacks in the groove. With the constant bead thickness routine, the shape of the tacks will be carried up through each layer, possibly resulting in a finish layer of varying thickness. In an attempt to correct this problem, a constant end face volume routine was implemented in place of the constant bead thickness routine. In this routine, a constant bead thickness is maintained unless the computer detects a rapid change in groove depth. When this occurs, the change in depth is subtracted from or added to the current bead thickness. The computer makes adaptive changes in AC, dwell, travel speed, etc. , to compensate for the new bead thickness. These changes are accomplished to the extent possible within the allowable heat input range. Successful implementation of this routine should help to automatically produce level beads even though the depth of the groove varied at some point during welding.

Restarting Problems

One of the problems found with restarting a weld was the inability to model the actual portion of the groove to be welded; modeling on the crater of the partially deposited bead was required. This resulted in an incorrect model of the groove at the start location. The software was modified to allow the groove to be modeled at any location along the length of the weld. After the modeling is complete, the operator can move the start position to the point desired. By modeling the groove a short distance ahead of the crater of the partial bead and restarting the arc on the crater, oscillation and welding parameters closer to those desired may be obtained sooner than if modeling had been performed on the crater itself.

Improve Tracking Adjustment

The limit on the number of consecutive corrections of oscillation position was eliminated to allow more flexibility in tracking adjustment.

10.0 Evaluation of Upgraded M-1000 (December 1983-April 1984)

Sixteen 1 in. thick test plates were welded between December 1983 and April 1984 using the upgraded M-1000. During this period, four different revisions of adaptive software were used. The root gaps used ranged from 1/8 to 3/4 in.; the included angle was held constant at 45°. 250 ipm wire feed speed was used exclusively.

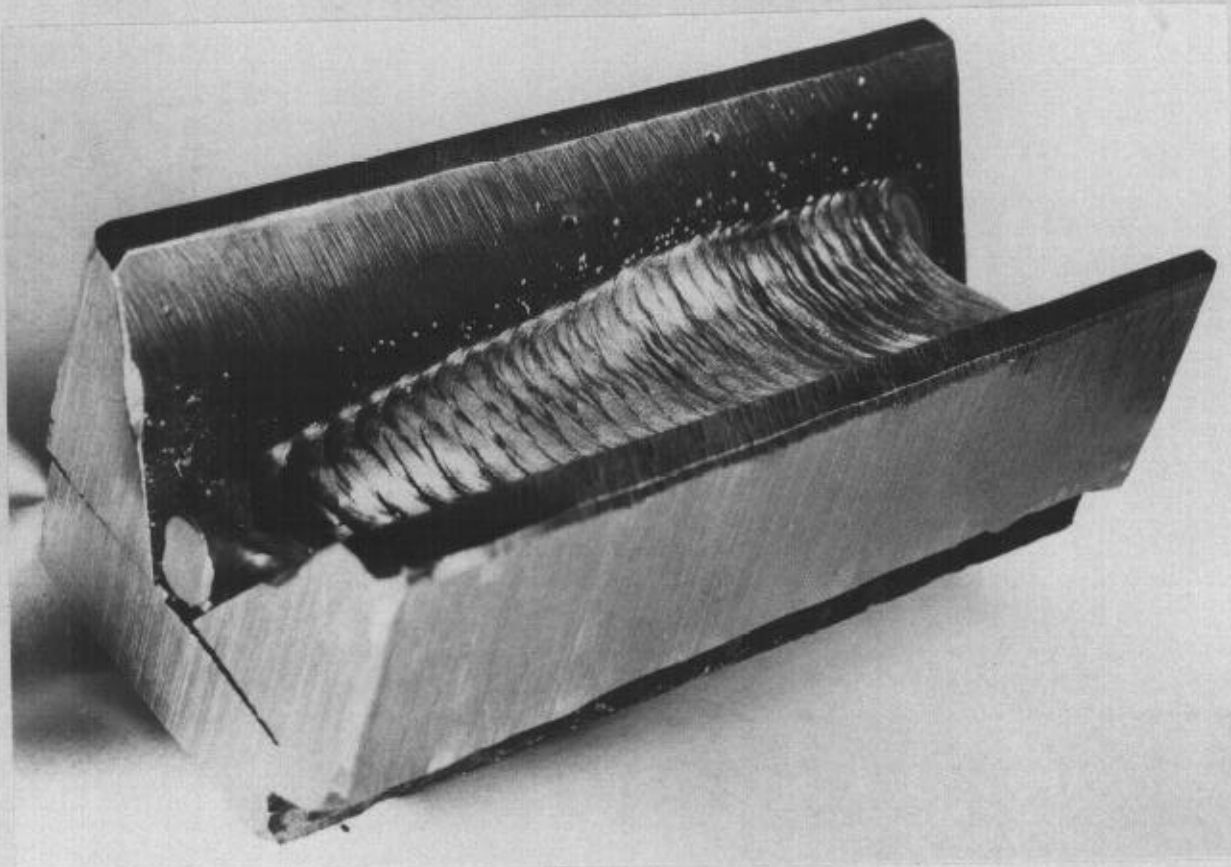
Results of the weld tests were encouraging in that good quality fill passes, both single and split bead, could be deposited and the startup routine was much simpler to use. The automatic modeling routines performed well and generally made the correct decisions as to the type of bead required. The width and oscillation centerline adjustments now possible with the last fill and finish pass routines also appeared to function satisfactorily. Finally, higher heat inputs were used than before the M-1000 update, resulting in larger size weld beads. However, although the results showed that significant progress had been made, serious problems still remained with bead shape, root pass penetration, contact tip life, arc starting and restarting, tracking response, and inadequate cleaning for proper operation of the modeling routines. Each of these problems will be discussed below.

1) Bead Shape/Quality Problems

When used with the last revision software tested, travel speeds were generally in the range desired to maximize the bead size and minimize the number of beads required. However, there were deficiencies in bead shape and quality, especially with root and finish passes. With root gaps less than 1/2 in., incomplete root penetration consistently resulted, although bead contours were generally flat. This problem appears to be related to the manner in which the M-1000 adjusts its contact tip to work distance. The M-1000 adjusts its tip to work distance based on current and voltage samples obtained at the centerline position of the oscillation stroke. When the arc mainly impinges on the leading edge of the weld puddle as the torch position crosses centerline, the current and voltage samples reflect the physical contact tip to work distance. However, if the bead thickness is increased, the arc tends to ride up somewhat more on the surface of the puddle. With standard mechanized welding, the physical tip to work distance may be mechanically held at the same distance as if the bead thickness were less. However, with the M-1000, the tip to work distance is actually the distance from the tip to the point where the arc impinges on the molten metal. Thus, if the arc is riding up on the surface of the puddle, the tip to backing bar (or underbead surface) distance will be greater than desired. This greatly reduces the penetration into the backing bar or underbead surface. (It should be noted that this is usually not a problem with vertical mechanized welding because the tip to work distance is maintained with respect to the underbead surface). In addition, because the arc is riding too high up on

the puddle, the oscillation width (driven by the requirement to perform sidewall tracking) will be greater than OPTimum. This further reduces the penetration into the root because the arc must penetrate through a greater thickness of base metal to reach the backing bar. At this point, the M-1000 was found to respond in one of two ways. The more common response was for the oscillation width to continue to increase (as a result of the high AC used and the riding up on the puddle), and the travel speed to slow down in response to the increasing width. When the maximum allowed heat input for that bead is reached, the oscillation width continues to increase. This results in a decrease in the puddle thickness, which then causes the torch to drive in towards the weld puddle to maintain the required tip to work distance. This causes the physical tip to work distance to decrease. In response to the decrease in physical tip to work distance, the arc now impinges higher up on the sidewalls than required to satisfy AC. This causes a decrease in the oscillation width and an increase in travel speed. After a short period of time the cycle repeats itself.

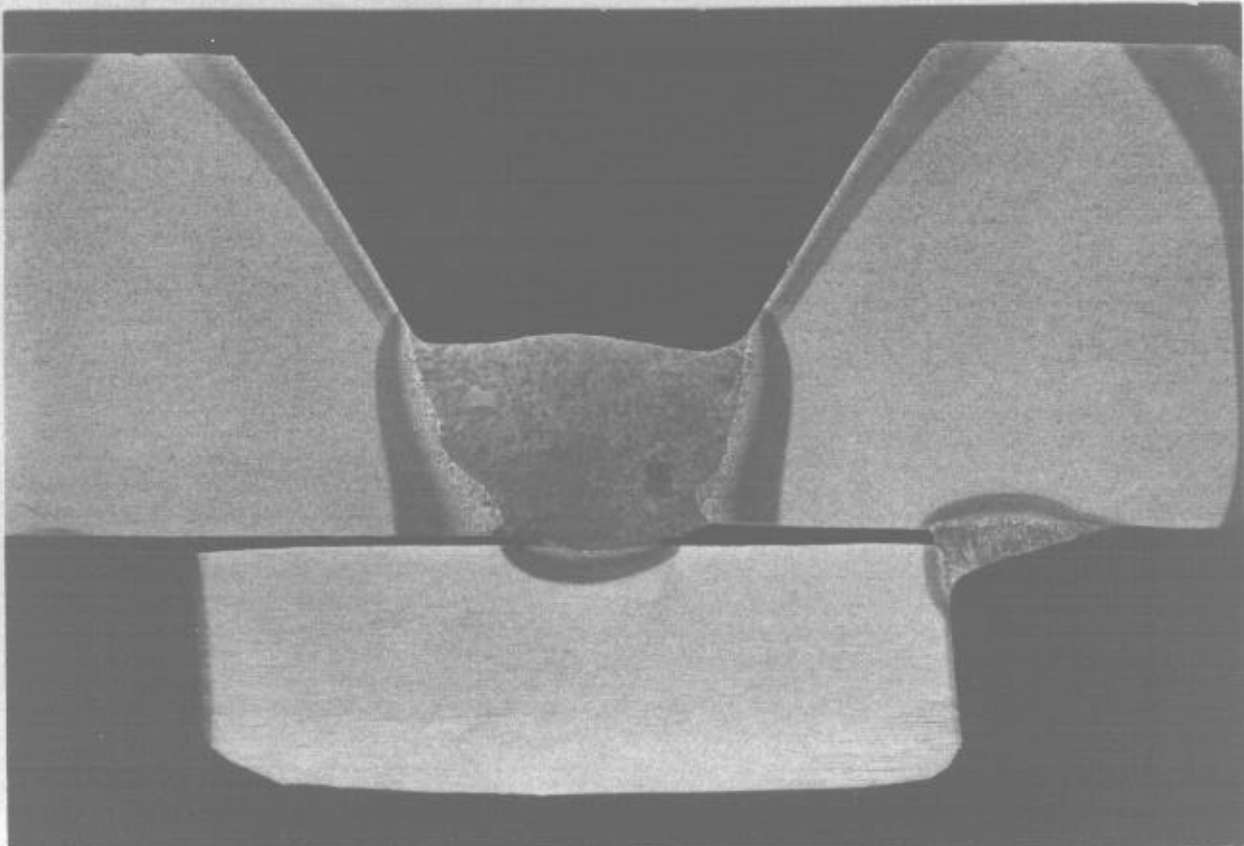
The other observed response to the arc riding too high up on the puddle is for the physical tip to work distance to slowly increase accompanied by an increase in the oscillation width and the corresponding decrease in travel speed. This occurs up to the point when the maximum heat input is reached. Unlike the former case, the parameters hold steady for the remainder of the joint, as long as the groove dimensions do not change. This phenomenon is illustrated in Figure 19. In this constant root gap (1/4 in.) joint, the oscillation width is shown to increase along the length of the weld. Macrosections from a similar weld are shown in Figures 20 and 21. Figure 20 was removed from a point near the weld start, while Figure 21 represents a



Magnification ~1X

Photograph of 1/4 in. Root Gap Test Weld
Showing Effects of Slowing Down of Travel Speed
Due To Arc Riding Too High on Puddle.
(Adaptive Software)

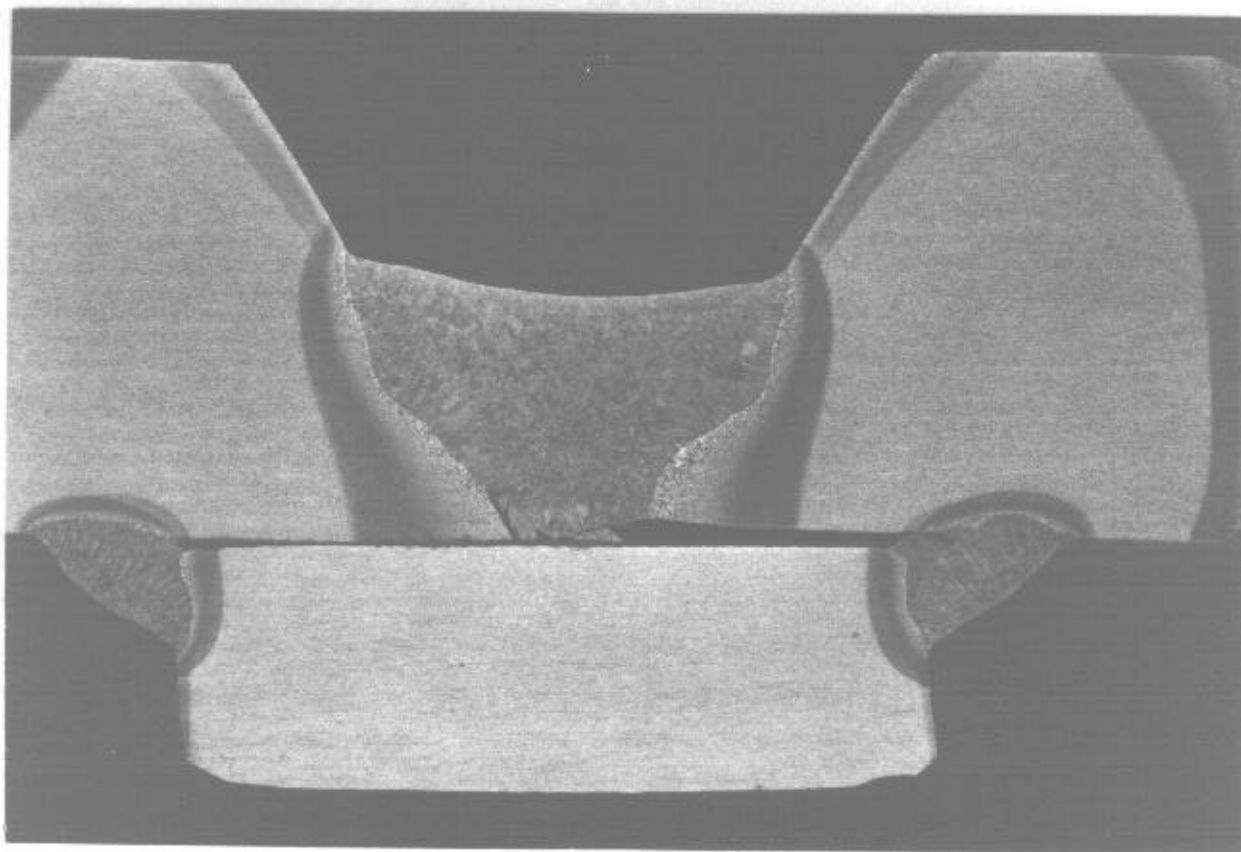
Figure 19



Magnification 2.5X

Photomicrograph of 1/4 in. Root Gap
Test Weld Near Start Location (Similar
to Weld in Figure 19).
(Adaptive Software)

Figure 20



Magnification 2.5X

Photomicrograph of 1/4 in. Root Gap Test Weld Near
Stop Location (Similar to Weld in Figure 19)
(Adaptive Software)

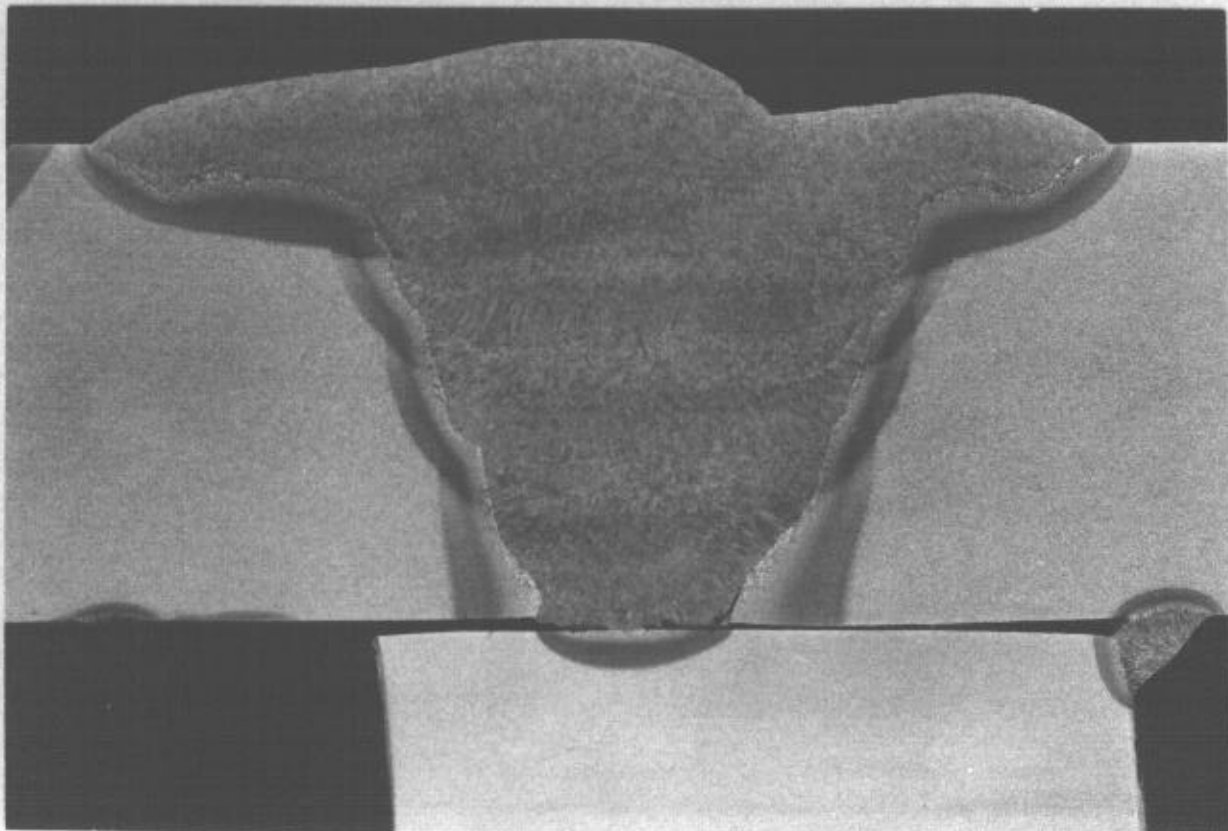
Figure 21

point near the weld stop. It is clearly shown in Figure 20 that only minimal penetration into the backing bar occurred. In Figure 21, no backing bar penetration took place and, in fact, there was lack of fusion against the bevel at the root. Although a root pass as shown in Figure 20 is technically acceptable, it is so close to being unacceptable that the quality of actual production root passes could not be guaranteed.

The problems described above can be reduced or eliminated by reducing the heat input. However, this will increase welding times by increasing the number of beads required.

Figures 22, 23 and 24 show photomacrographs of welds with root gaps of $3/8$, $1/8$ and $1/4$ in. , respectively. These welds were produced with the last revision of adaptive software tested. Generally root pass penetration was marginal to unacceptable but root pass shape was good. On all three test plates, the travel speed either started out fast then slowed down or started out slow then increased. This resulted in uneven fill over the length of the joint. Because of this, the fill passes (which used automatic tracking and adaptive control), all followed the trend of the root pass. That is, the uneven root pass thickness was carried up through all the fill passes meaning that when the joint was nearly flush on one end, it was up to $1/4$ in. underf lush on the other end. Since finish passes are deposited without the ability to change the travel speed, uneven reinforcement height resulted.

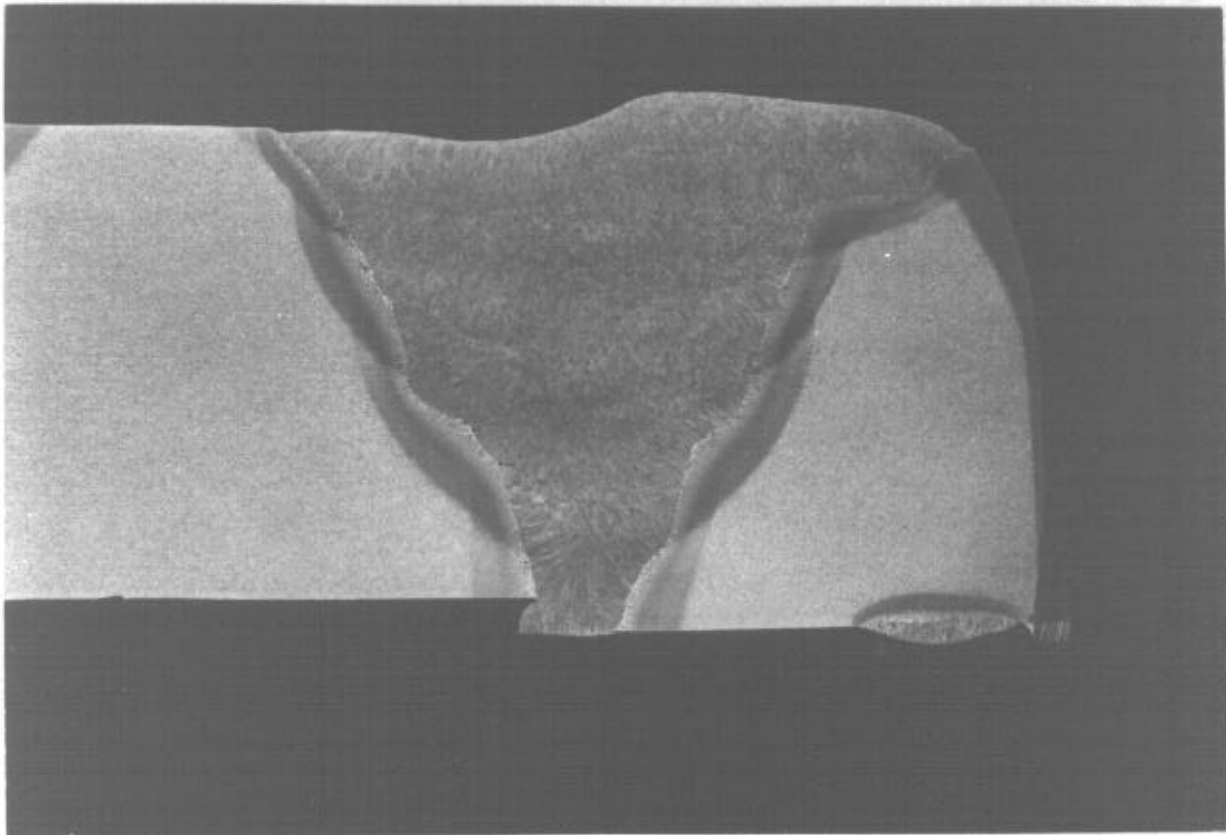
As shown in Figures 22-24, quality fill passes were deposited. Bead sizes were reasonably close to those deposited using the manual input program (Table 11). Bead shapes were generally satisfactory. However, finish pass



Magnification 2.5X

Photomicrograph of 3/8 in. Root Gap Test Weld 40T
(Adaptive Software)

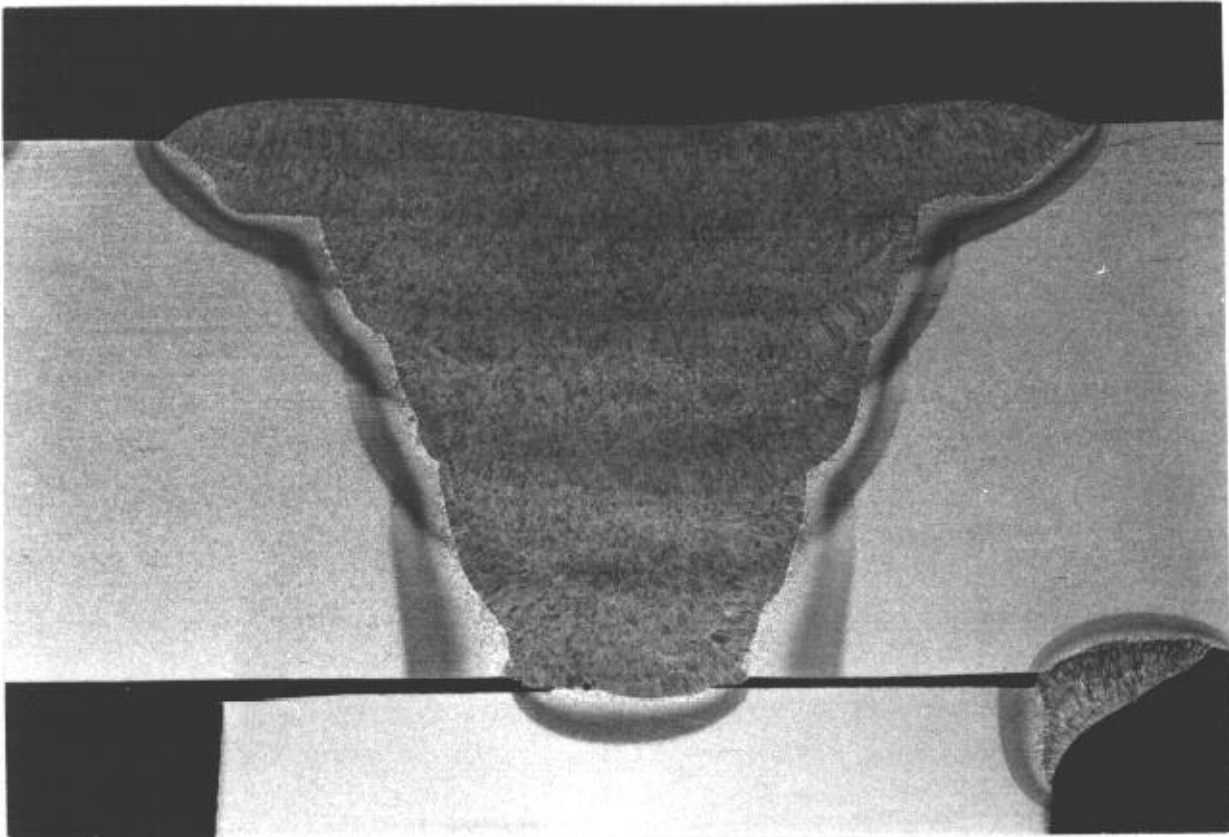
Figure 22



Magnification 2.5X

Photomacrograph of 1/8 in. Root Gap Test Weld 41T
(Adaptive Software)

Figure 23



Magnification 2.5X

Photomicrograph of 1/4 in. Root Gap Test Weld 42B
(Adaptive Software)

Figure 24

shapes were less than ideal. Single bead finish passes tended to have too much metal at the toes and were concave near the center. Split bead finish passes tended to be overly convex and generally produced excessive reinforcement. This was caused by the choice of less than optimum oscillation parameters by the algorithms.

In summary, problems with root pass penetration and maintenance of constant root pass parameters existed. Fill passes were generally of good quality with good bead shapes. Finish bead shapes were generally undesirable. Bead by bead heat inputs were close to those considered Optimum. Overall, significant improvements were made in bead size and shape over software available prior to the M-1000 upgrade.

2) Arc Starting and Restarting

Occasionally porosity appeared at the start. This was caused by an excessive gas cup to work distance during the four oscillation cycle period at the start where current and voltage samples are taken and during the following oscillation cycles where the computer is making adjustment in width, tip to work distance, etc. It should be noted that the contact tip must be extended at least $3/32$ in. past the end of the gas cup to allow it to make electrical contact with the base plate surface during modeling. This requirement results in greater cup to work distances than in mechanized welding and contributes to poorer shielding.

The new restart routine which allows modeling at any location and restarting at any location was tested. Although the routine worked well, the problem previously described with the delay in assuming proper tip to work distance was still present. As a result, by the time the proper contact tip to work distance was established, the arc was well past the restart point.

3) Uneven Fill Height

In mechanized welding, it is desirable to have a relatively constant depth of groove remaining along the weld length before depositing finish passes. It was hoped that the M-1000 with the "constant end face volume" routine previously discussed would provide this automatically. On test plates where the root pass thickness varied along the length, this condition was carried up through the finish layer. The reason for this was that in order for the computer to detect that a change in bead thickness is required, the underbead profile must change by at least 0.100 in. over two consecutive oscillation sweeps. For a typical travel speed of 2 ipm and oscillation period of 3.9 sec. , a height change of 0.100 in. over 0.131 in. of travel (37°) is required. This is a relatively steep incline which may only occur with some tacks or starts/stops.

4) Tracking Response

Using the last revision program, tracking appeared to work well in single bead root and fill passes. Tracking response was not tested.

5) Cleaning Requirements

Extremely good cleaning was required in the area to be modeled to prevent mis-modeling and/or bad starts. This was especially true when extensive modeling of the groove was required, such as for split bead fill passes or finish passes. Generally light burring or grinding was required to inaugurate a successful modeling routine.

NOTE: The following observations were made using the upgraded M-1000 hardware with the manual input software. Vertical position test plates 50 to 75 in. long were welded at heat inputs up to 110 kJ /in. Automatic and manual tracking beads were both possible with this program.

6) Contact Tip Life

As discussed in Section 8.2, the contact tip life was 20 to 60 arc minutes. This was based on arc appearance and quality. However, while welding the 75 in. test plates, several new factors appeared. Using automatic tracking, the arc quality would start to degrade slightly after 15 to 20 arc minutes. This was indicated by an increase in amperage and voltage ranges on chart recorder traces (Figure 25). Coincident with this was the beginning of tracking problems. This was characterized by excessive corrections of the arc position with respect to the sidewalls which increased in frequency as the arc time on the tip increased. Several times the bead shape was affected to the point where it became unacceptable (usually overly convex), and welding had to be stopped to change the contact tip. In beads deposited using manual tracking, arc quality also began to degrade after 15 to 20 arc minutes (see Figure 26). However, welding could be successfully continued for the duration of the bead because manual tracking was used. Thus, when automatic tracking is used, contact tip life is measured by how long tracking can be successfully performed. With manual tracking, contact tip life is measured by how long acceptable arc characteristics can be maintained. It is estimated that tip life with automatic tracking is about 50% of that with manual tracking.

7) Travel Drive and Oscillator Problems

Mechanical problems were encountered with the travel drive and oscillator assemblies. On three occasions, bearings in the travel drive assembly

VOLTAGE —————→
100 V FULL SCALE

← START OF
TRACKING PROBLEMS

24 IN/HR
CHART SPEED

0 VOLTS —→
AND AMPS

← AMPERAGE
250 A FULL SCALE

AUTOMATIC TRACKING
CURRENT/VOLTAGE TRACE

Directed as 110 A

of industrial film

low

Control Inc.

VOLTAGE
100 V FULL SCALE

AMPERAGE
250 A FULL SCALE

24 IN/HR
CHART SPEED

0 VOLTS
AND AMPS

MANUAL TRACKING
CURRENT/VOLTAGE TRACE

FIGURE 26

failed. This is considered serious based on the relatively low number of hours of use between failures and because failure of a bearing may disengage the drive motor from the drive wheels. This makes the travel carriage "free

the full extent of the stroke, and sudden shifts in oscillation centerline position (up to in.) during the course of welding. These problems were caused by small amounts of shop dirt on the oscillator shaft or misalignment of the oscillator shaft. These problems arise with enough frequency to be considered a serious problem.

8) Automatic Stoppage of Welding

The M-1000 has built-in software routines to detect fault conditions such as electrical shorts, inechnical limits on torch and oscillator positions, loss of communication between travel carriage and computer, loss of current (welding current below 100 amps), loss of voltage (arc voltage below 15.0 volts), etc. This fault detection is required for automatic, unattended operation of the unit. However, during the course of the evaluation program, welding was automatically stopped on several occasions with the report of "loss of voltage" or "loas of current". Although the computer may have detected the current or voltage loss for a moment due to spatter momentarily shorting the contact tip or the filler wire momentarily touching the weld puddle, these are not reasons to stop welding. Therefore it is believed that some re-examination of the automatic stop routines is in **order.**

9) Effect of Shop Environment

The wire feed unit and torch housing were found to be poorly sealed from shop dirt, including metal chips from grinding and burring. Small amounts of metal chips found their way inside of the torch housing and were attracted to the magnet used to signal the torch "home" position to a hall effect switch. This resulted in problems with extending the torch. Metal chips also easily found their way into places around the wire feed drive rolls which produced "short" faults or made it impossible to perform the modeling routine. The same problem also occurred with metal chips forming a short between the travel carriage case and the copper block which accepts the water and gas hoses and the positive power supply lead. Finally, as previously mentioned, shop dirt on the oscillator shaft contributed to oscillation problems. It is believed that the frequency of problems caused by shop dirt would be intolerable in an actual production environment based on what was observed in the welding laboratory environment.

11.0 Summary and Conclusions

The M-1000 concept of thru-the-arc seam tracking and adaptive control was found to be a viable technology as evidenced by the many test plates welded. In addition, software was demonstrated that was capable of making correct, logical decisions as to type of bead required and welding parameters to be used. Potential savings in welding costs could be realized through an increase in operator factor if the M-1000 could be made competitive with mechanized equipment in terms of weld quality and bead size deposited.

however, major software and hardware problems were found which effectively limit serious production implementation at this time. Software problems included:

- Non-optimum welding parameters on root and finish passes resulting in quality and/or bead shape problems.
- Controlling the physical contact tip to work distance (especially when the arc rides up on the puddle).
- Starting problems (porosity, poor initial bead shape and quality).
- Restarting problems (porosity, poor fusion at start location).
- The requirement for at least 0.350 in. of sidewall for successful tracking with high heat input PGMAW.
- Problems associated with overall uneven level of fill with respect to the plate surface due to deposition of constant thickness beads.
- Slow tracking response with respect to sudden sidewall gouges and changes in underbead height.
- Unnecessary automatic stoppage of welding due to momentary "loss of current" or "loss of voltage".

Hardware problems included:

- Inability to automatically track reliably after contact tip starts to wear. (Note that at this time the tip is still capable of depositing sound metal with manual tracking.)
- Inaccurate travel speed caused by drive wheel slippage which varies with each set of wheels used.

- 1 A travel drive system prone to mechanical failure.
- 1 An oscillator system overly sensitive to shop dirt and mechanical misalignment.
- 1 Inadequate sealing of components from shop dirt which results in frequent mechanical and electrical problems.

Three additional potential problems must also be addressed:

1) Root Gaps Less Than 1/8 in. :

A potential problem exists with automatic tracking of root passes in joints with less than 1/8 in. root gap. In order to track, the physical oscillation width must be at least 1/8 in. With less oscillation width, the computer may get erroneous current samples at the centerline due to arc flare or the arc impinging partly on both sidewalls. In order to fully penetrate roots with gaps less than 1/8 in. , it is frequently necessary to deposit a stringer bead or to oscillate only slightly. With the requirement for a minimum 1/8 in. physical oscillation width, it appears that full penetration root passes with automatic tracking may not be possible in joints with less than 1/8 in. root gap.

2) Root Passes Deposited Over Ceramics or With Open Root Technique:

Deposition of root passes using an open root technique or ceramic backing materials may be more difficult for the M-1000 compared to using a backing bar. Using an open root or ceramics, a very fine balance exists between root pass quality and welding parameters, especially travel speed, tip to work distance, and oscillation width and velocity. Small changes in root gap along the joint length require changes in parameters to keep from "blowing through" or stubbing the electrode into the ceramics.

With the M-1000, potential problems exist with sensing these changes and making appropriate adjustments fast enough to continue successful welding. This potential problem is related to the speed of tracking correction and. possible problems with differentiating between the actual sidewall at the root and puddle wash or the keyhole formed when proper open root and ceramic backed welding techniques are used.

3) Tracking Bead to Bead

In thick plate joints, a point arises during welding when a sidewall may not always be available for tracking, such as with three or four bead wide layers. In order to deposit the large size beads obtained with high wire feed speeds and high heat inputs, a substantial amount of sidewall is required to maintain automatic tracking. It is unlikely that successful automatic- tracking could be carried out using the side of a previously deposited bead for tracking because it is likely that inadequate geometry exists to prevent erosion of the side of the bead by the arc.

12.0 Recommendations

Work should be continued to develop this promising technology to the point where it is competitive with existing mechanized equipment operated by a good welder with a good welding procedure.

Initial work should concentrate on: (1) reducing the sensitivity of automatic tracking to contact tip condition; (2) improving the reliability and. accuracy of the travel drive; (3) improving the oscillator reliability; (4) reducing hardware problems due to shop dirt; (5) optimizing the algorithms describing the welding technique, especially for root and finish passes and (6) improving starting and re-starting.